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ANL/EVS/AGEM/TR-07-11

Interim Measure Conceptual Design for Remediation at the Former CCC/USDA Grain Storage Facility at Centralia, Kansas: Pilot Test and Remedy Implementation

Environmental Science Division

USDA United States Department of Agriculture

Work sponsored by Commodity Credit Corporation,
United States Department of Agriculture

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Interim Measure Conceptual Design for Remediation at the Former CCC/USDA Grain Storage Facility at Centralia, Kansas: Pilot Test and Remedy Implementation

by
Applied Geosciences and Environmental Management Section
Environmental Science Division, Argonne National Laboratory

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United States Department of Agriculture

Work sponsored by Commodity Credit Corporation,
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Notation

BER	Bureau of Environmental Remediation (KDHE)
BGL	below ground level
°C	degree(s) Celsius
CCC	Commodity Credit Corporation
CPT	cone penetrometer
EPA	U.S. Environmental Protection Agency
ft	foot (feet)
hr	hour(s)
IM	Interim Measure
in.	inch(es)
ISCR	*in situ* chemical reduction
KDHE	Kansas Department of Health and Environment
lb	pound(s)
µg/kg	microgram(s) per kilogram
mg/kg	milligram(s) per kilogram
µg/L	microgram(s) per liter
MCL	maximum contaminant level
min	minute(s)
MNA	monitored natural attenuation
mV	millivolt(s)
ORP	oxidation-reduction potential
ppb	part(s) per billion
PVC	polyvinyl chloride
RBSL	Risk-Based Screening Level
USDA	U.S. Department of Agriculture
VOC	volatile organic compound
yr	year(s)
ZVI	zero-valent iron

Interim Measure Conceptual Design for Remediation at the Former CCC/USDA Grain Storage Facility at Centralia, Kansas: Pilot Test and Remedy Implementation

Executive Summary

This document presents an Interim Measure Work Plan/Design for the short-term, field-scale pilot testing and subsequent implementation of a non-emergency Interim Measure (IM) at the site of the former grain storage facility operated by the Commodity Credit Corporation of the U.S. Department of Agriculture (CCC/USDA) in Centralia, Kansas. The IM is recommended to mitigate both (1) localized carbon tetrachloride contamination in the vadose zone soils beneath the former facility and (2) present (and potentially future) carbon tetrachloride contamination identified in the shallow groundwater beneath and in the immediate vicinity of the former CCC/USDA facility.

Investigations conducted on behalf of the CCC/USDA by Argonne National Laboratory have demonstrated that groundwater at the Centralia site is contaminated with carbon tetrachloride at levels that exceed the Kansas Tier 2 Risk-Based Screening Level (RBSL) and the U.S. Environmental Protection Agency's maximum contaminant level of 5.0 μg/L for this compound. Groundwater sampling and analyses conducted by Argonne under a monitoring program approved by the Kansas Department of Health and Environment (KDHE) indicated that the carbon tetrachloride levels at several locations in the groundwater plume have increased since twice yearly monitoring of the site began in September 2005. The identified groundwater contamination currently poses no unacceptable health risks, in view of the absence of potential human receptors in the vicinity of the former CCC/USDA facility.

Carbon tetrachloride contamination has also been identified at Centralia in subsurface soils at concentrations on the order of the Kansas Tier 2 RBSL of 200 μg/kg in soil for the soil-to-groundwater protection pathway. Soils contaminated at this level might pose some risk as a potential source of carbon tetrachloride contamination to groundwater.

To mitigate the existing contaminant levels and decrease the potential future concentrations of carbon tetrachloride in groundwater and soil, the CCC/USDA recommends initial short-term, field-scale pilot testing of a remedial approach that employs *in situ* chemical reduction (ISCR), in the form of a commercially available material marketed by Adventus Americas, Inc., Freeport, Illinois (http://www.adventusgroup.com). If the pilot test is successful, it will be followed by a request for KDHE authorization of full implementation of the ISCR approach.

In the recommended ISCR approach, the Adventus EHC® material — a proprietary mixture of food-grade organic carbon and zero-valent iron — is introduced into the subsurface, where the components are released slowly into the formation. The compounds create highly reducing conditions in the saturated zone and the overlying vadose zone. These conditions foster chemical and biological reductive dechlorination of carbon tetrachloride. The anticipated effective lifetime of the EHC compounds following injection is 1-5 yr.

Although ISCR is a relatively innovative remedial approach, the EHC technology has been demonstrated to be effective in the treatment of carbon tetrachloride contamination in groundwater and has been employed at a carbon tetrachloride contamination site elsewhere in Kansas (Cargill Flour Mill and Elevator, Wellington, Kansas; KDHE Project Code C209670158), with the approval of the KDHE.

At Centralia, the CCC/USDA recommends use of the ISCR approach initially in a short-term pilot test addressing the elevated carbon tetrachloride levels identified in one of three persistently highly contaminated areas ("hot-spot areas") in the groundwater plume. In this test, a three-dimensional grid pattern of direct-push injection points will be used to distribute the EHC material (in slurry or aqueous form) throughout the volume of the contaminated aquifer and (in selected locations) the vadose zone in the selected hot-spot area. Injection of the EHC material will be conducted by a licensed contractor, under the supervision of Adventus and Argonne technical personnel. The contractor will be identified upon acceptance by the KDHE of the conceptual design presented here. In the pilot test, Argonne will install and periodically sample a network of temporary and permanent monitoring points to document (1) the contaminant distribution in the saturated and vadose zones prior to injection, (2) the distribution of the EHC material in these zones immediately following injection, and (3) subsequent changes in contaminant concentrations that occur over time in response to the imposed treatment.

Argonne's investigations have shown that the lithologic properties of the unit hosting the contaminated aquifer at Centralia vary both vertically and laterally, resulting in a heterogeneous distribution of permeabilities and relatively restricted groundwater movement across much of the site. The initial short-term pilot test in the most contaminated of the three hot-spot areas is recommended to identify the operational techniques that will be required for optimal implementation and monitoring of the ISCR approach in the other two hot-spot areas and to verify the suitability of this approach for treating the carbon tetrachloride contamination at the Centralia site.

The results of three months of monitoring following injection of the EHC material in the pilot test area will be presented for review by the CCC/USDA and KDHE project managers.

1 Introduction

This document presents an Interim Measure Work Plan/Design for the short-term, field-scale pilot testing and subsequent implementation of a non-emergency Interim Measure (IM) at the site of the former grain storage facility operated by the Commodity Credit Corporation of the U.S. Department of Agriculture (CCC/USDA) in Centralia, Kansas. The IM is recommended to mitigate both (1) localized carbon tetrachloride contamination in the vadose zone soils beneath the former facility and (2) present (and potentially future) carbon tetrachloride contamination identified in the shallow groundwater beneath and in the immediate vicinity of the former CCC/USDA facility.

The conceptual design presented here was developed in accordance with the Kansas Department of Health and Environment (KDHE), Bureau of Environmental Remediation (BER), Policy #BER-RS-029, *Policy and Scope of Work: Interim Measures* (KDHE 1996).

1.1 Site Background

In April 1998, the KDHE sampled a private domestic well at the Morris residence near Centralia as part of the CCC/USDA private well sampling program. This program had been initiated to determine whether carbon tetrachloride was present in domestic wells located near former CCC/USDA grain storage facilities in Kansas (Figure 1.1). Carbon tetrachloride was detected and confirmed in the Morris well at a concentration of 25.4 μg/L. The sampling occurred on April 14, 1998, during the CCC/USDA private well sampling program. This concentration exceeds the Kansas Tier 2 Risk-Based Screening Level (RBSL) and the U.S. Environmental Protection Agency (EPA) maximum contaminant level (MCL) of 5.0 μg/L for carbon tetrachloride. On the basis of these findings, the KDHE conducted further preliminary studies in 1998 and identified carbon tetrachloride contamination on and near the site of a former CCC/USDA grain storage facility located approximately 3,500 ft south of the contaminated private well (Argonne 2002a). No grain storage or other structures associated with the former CCC/USDA facility remain at the site; it is presently vacant pastureland.

At the request of the CCC/USDA, Argonne subsequently conducted a phased series of investigations (from 2002 to 2004) to characterize the hydrogeologic setting and the distribution of carbon tetrachloride contamination at the former CCC/USDA facility (Argonne 2003, 2004). The results of these studies and subsequent monitoring activities are summarized in Section 1.2.

1.2 Results of Previous Investigations

Purge-and-trap analyses of near-surface and deeper subsurface vadose zone soil samples collected by Argonne at the former CCC/USDA facility in 2002 and 2003 (Figures 1.2 and 1.3, respectively; originally reported in Argonne 2003, 2004) detected no concentrations of carbon tetrachloride in soils at levels exceeding the Kansas RBSLs for direct contact under either the residential or the non-residential exposure scenario (2.5 mg/kg or 7.0 mg/kg, respectively; KDHE 2007a). Carbon tetrachloride contamination was identified in subsurface soils at concentrations greater than 100 μg/kg in three small areas around locations SB06, SB12, and SB24 (Figure 1.3). Maximum carbon tetrachloride levels in vadose zone soils ranging from 202 μg/kg to 219 μg/kg were identified over a depth interval of approximately 20 ft at one location only (SB12); these levels are on the order of the Kansas Tier 2 RBSL of 200 μg/kg in soil for the soil-to-groundwater protection pathway (KDHE 2007a), and hence they may pose some risk as a potential source of carbon tetrachloride contamination to groundwater.

The results of groundwater characterization studies performed by Argonne (2003, 2004) demonstrated carbon tetrachloride contamination associated with the former CCC/USDA grain storage facility at levels above the RBSL and the MCL. The contamination occurs in a shallow aquifer consisting of glacial outwash sediments ranging from fine grained silts and clay to gravely, medium to coarse sands (Figure 1.4). The identified groundwater plume is limited in extent and is unrelated to the contamination originally identified by the KDHE at the Morris private well. The contamination in groundwater at the former CCC/USDA facility is restricted vertically to the upper portion of the saturated zone (Figure 1.4) and laterally to the vicinity of the former facility boundary (Figure 1.5). Whether the contamination in the Morris private well has been investigated or resolved is unknown.

High levels of chloroform (in comparison to carbon tetrachloride) were detected at several locations in the groundwater plume during the phased characterization studies (Argonne 2003, 2004). Together with the observed aquifer heterogeneity and plume morphology (see below), the relative abundance of chloroform suggests that the rates of groundwater flow and contaminant migration at the former CCC/USDA facility are limited. The relative concentrations of chloroform, a primary degradation product of carbon tetrachloride, suggest that some degree of reductive dechlorination or natural biodegradation of carbon tetrachloride might be taking place *in situ* at the former CCC/USDA facility. The probability of observing this anaerobic process is increased in groundwater systems that experience restricted circulation and limited mixing with recent, oxygenated waters.

With the approval of the KDHE, a network of 12 permanent groundwater sampling and monitoring points (piezometers SB01, SB04, SB05, SB07, SB08, and SB09, as well as monitoring wells MW1-MW6; Figure 1.6) was established in 2004 (Argonne 2005b). The purposes of this network were to (1) confirm the lateral extent of the carbon tetrachloride plume, (2) track any contaminant migration that might occur, and (3) provide sampling points for the collection of geochemical data that could be used to evaluate the *in situ* potential for natural attenuation of the existing plume. Initial sampling of the complete monitoring network was performed in August 2004 (Figure 1.6). A preliminary quantitative screening of the August 2004 results with the technical protocol for evaluation of natural attenuation of chlorinated solvents in groundwater (EPA 1998) indicated that conditions at some locations in the aquifer might be suitable for natural *in situ* biodegradation of carbon tetrachloride through reductive dechlorination (Table 4.1 in Argonne 2005b). A second evaluation based on March 2006 data (as well as dissolved hydrogen values obtained in September 2005) gave somewhat higher scores, but the evidence for reductive dechlorination was still “limited” (Table 1.1; see also Argonne 2006a).

The carbon tetrachloride plume at Centralia does not exhibit the elongated geometry typically associated with groundwater flow and advection-dominated contaminant migration. Instead, the areal distribution of carbon tetrachloride in the groundwater plume is highly heterogeneous, with the most elevated, most persistent concentrations (greater than 100 μg/L in recent monitoring) occurring in three seemingly isolated hot-spot areas. These areas are located near the north-central (SB08-MW02), western (SB05), and southwestern (SB01) boundaries of the former facility (Figure 1.7). These observations are consistent with groundwater levels, estimated hydraulic conductivity values (Appendix A), and apparent hydraulic gradients determined for the site (Figure 1.8). All of these data confirm that groundwater movement beneath much of the former CCC/USDA facility is sluggish. Flow rates were estimated on the basis of the slug tests results reported in Appendix A and water levels measured on June 16, 2006 (Figure 1.8). The resulting flow rates were ≤ 0.2 ft/day and < 1.0 ft/day, respectively, near the southern and western margins of the former CCC/USDA facility. In the eastern part of the property, the gradient is low but uncertain, and no estimates of flow rate could be made.

With the approval of the KDHE, the CCC/USDA initiated a program of extended groundwater geochemical sampling and water level monitoring at Centralia in September 2005 (Argonne 2005a,c). The monitoring was recommended for a 2-yr period. The objectives of this

TABLE 1.1 Scoring of biodegradation processes at Centralia — March 2006 data.[a]

		MW01		MW02		MW03		MW04		MW05		MW06		MW07		MW08	
Constituent	Units	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points
Dissolved Oxygen	mg/L	9.33	-3	1.24	0	9.39	0	6.82	-3	0.9	0	9.87	-3	0.34	3	5.32	-3
Nitrate	mg/L	0.82	2	9.92	0	9.17	0	4.97	0	3.36	0	0.524	2	1.18	0	2.47	0
Iron(II)	mg/L	0.04	0	0	0	0	0	0.06	0	0.06	0	0.02	0	0.03	0	0	0
Sulfate	mg/L	6.3	2	12.2	2	9.15	2	6.38	2	5.17	2	5	2	28.5	0	14.4	2
Sulfide	mg/L	< 0.02	0	0.0381	0	<0.02	0	0.0794	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0
Methane	mg/L	< 0.002	0	0.034	0	< 0.002	0	0.051	0	< 0.002	0	0.0023	0	< 0.002	0	< 0.002	0
ORP	mV	297	0	295	0	290	0	283	0	156	0	263	0	143	0	145	0
pH	–	7.56	0	6.78	0	6.75	0	7.78	0	6.9	0	7.38	0	6.61	0	6.35	0
Total Organic Carbon	mg/L	6.19	0	3.57	0	1.23	0	5.07	0	5.54	0	4.12	0	35.4	2	9	0
Temperature	°C	14.3	0	14.2	0	13.8	0	13.5	0	14.3	0	14.1	0	14.7	0	13.5	0
Carbon Dioxide[b]	mg/L	30	0	NR[c]	–	77	1	55	0	30	0	35	0	NR	–	NR	–
Alkalinity[b]	mg/L	325	0	364	0	353	0	337	0	304	0	343	0	299	0	342	0
Chloride[b]	mg/L	14.9	0	8.45	0	24	0	11.9	0	9.66	0	8.98	0	8.72	0	47.4	2
Dissolved Hydrogen	nM	NA[d]	–	3.1[e]	3	NA	–	NA	–	NA	–	NA	–	NA	–	NA	–
Chloroform	µg/L	ND[f]	0	21	2	0.2 J[g]	2	ND	0	ND	0	ND	0	0.6 J	2	ND	0
Dichloromethane (methylene chloride)	µg/L	ND	0	ND	0	ND	0	ND	0	ND	0	ND	0	ND	0	ND	0
	Total points =>		1		**7**		5		-1		2		1		**7**		1

TABLE 1.1 (Cont.)

		MW09		MW10		SB01		SB04		SB05		SB07R		SB08		SB09	
Constituent	Units	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points
Dissolved Oxygen	mg/L	0.95	0	6.42	-3	5.98	-3	5.96	-3	4.8	0	7.41	-3	3.4	0	1.53	0
Nitrate	mg/L	3.25	0	1.23	0	1.14	0	3.07	0	2.56	0	1.27	0	1.69	0	4.67	0
Iron(II)	mg/L	0.09	0	0	0	0	0	NR	–	0.18	0	0.08	0	0	0	0	0
Sulfate	mg/L	6.23	2	10.8	2	4.87	2	5.98	2	2.96	2	16.8	2	9.25	2	38.8	0
Sulfide	mg/L	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0
Methane	mg/L	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0
ORP	mV	214	0	166	0	185	0	276	0	253	0	83	0	246	0	206	0
pH	–	7.33	0	6.6	0	7.3	0	7.57	0	7.67	0	7.24	0	7.14	0	7.03	0
Total Organic Carbon	mg/L	10.7	0	7.96	0	8.97	0	3.78	0	4.97	0	11.2	0	5.99	0	6.88	0
Temperature	^{o}C	17.7	0	14.8	0	12.4	0	13	0	13.3	0	16.8	0	12.9	0	11.7	0
Carbon Dioxide[b]	mg/L	55	0	65	1	55	0	30	0	40	0	60	1	40	0	99	1
Alkalinity[b]	mg/L	329	0	298	0	338	0	371	0	324	0	318	0	327	0	495	0
Chloride[b]	mg/L	6.39	0	74.3	2	22.5	0	40	2	57.1	2	30.4	2	19.3	0	15.6	0
Dissolved Hydrogen	nM	NA	–	NA	–	71[a]	3	24[a]	3	11[a]	3	NA	–	6.1[a]	3	NA	–
Chloroform	μg/L	ND	0	ND	0	5.7	2	0.5 J	2	7.2	2	2.7	2	2.7	2	ND	0
Dichloromethane (methylene chloride)	μg/L	ND	0	ND	0	ND	0	ND	0	ND	0	ND	0	ND	0	ND	0
	Total points =>		2		2		4		**6**		**9**		4		**7**		1

[a] Scoring is based on results for samples collected in March 2006. Points are interpreted as follows (EPA 1998):
0–5 Inadequate evidence for reductive dechlorination.
6–14 Limited evidence for reductive dechlorination.
15–20 Adequate evidence for reductive dechlorination.
> 20 Strong evidence for reductive dechlorination.

[b] For evaluation of alkalinity, carbon dioxide, and chloride, MW01 (because of its location) was selected to represent background levels. For these constituents, points are awarded when the concentration is greater than twice the background concentration.

[c] NR, not recorded.

[d] NA, not analyzed for dissolved hydrogen in March 2006.

[e] Dissolved hydrogen result from September 2005 sampling.

[f] ND, not detected at an instrument detection limit of 0.1 μg/L.

[g] Qualifier J indicates an estimated concentration below the method quantitation limit of 1.0 μg/L.

program are to (1) document the physical and geochemical evolution of the carbon tetrachloride plume and (2) collect data necessary to evaluate the viability of monitored natural attenuation (MNA) as a possible remedial option for this site. The monitoring program was designed to provide data in keeping with KDHE Policy #BER-RS-042 for the evaluation of MNA (KDHE 2001). Twice yearly sampling of groundwater for analyses for volatile organic compounds (VOCs) and selected geochemical indicator parameters required under Policy #BER-RS-042 began at the site in September-October 2005 (Argonne 2005c). At the request of the KDHE, the monitoring well network was expanded in January 2006 to include four additional monitoring wells, MW07-MW10 (Argonne 2006a; Figure 1.8).

Regular sampling continued in September 2006 (Argonne 2006b). The most recent sampling event, marking approximately 18 months of monitoring under this program, was completed in March 2007 (Argonne 2007). The results of VOCs analyses for groundwater samples collected during the monitoring program are summarized in Table 1.2, together with VOCs results for the initial sampling of the monitoring well network in August 2004. The March 2007 results are illustrated, in historical context, in Figure 1.7. The results of screening of the March 2007 data with the EPA protocol for evaluating natural attenuation (EPA 1998) are in Table 1.3.

Evaluation of the 2007 monitoring data according to the EPA (1998) protocol confirmed the earlier finding of limited quantitative evidence for natural degradation of carbon tetrachloride at some locations in the carbon tetrachloride plume at Centralia. Despite this observation, however, the concentrations of carbon tetrachloride at sampling locations in the plume have shown no significant decreases with time; carbon tetrachloride levels at most of the sampled locations in the plume, particularly those in the previously identified hot-spot areas (SB01, SB05, and SB08-MW02) have remained relatively unchanged or have increased significantly since the August 2004 sampling event (Table 1.2). Of the three identified hot-spot areas, only the location near monitoring well MW02 shows a possible association with carbon tetrachloride contamination identified in the overlying vadose zone soils (at investigative boring SB12, as described above). Figure 1.7 illustrates this relationship and also indicates slow expansion of the groundwater plume along its south and southwest margins. The estimated maximum extension of approximately 50 ft in the plume boundary (near MW04 and MW07) from August 2004 to March 2007 is in keeping with the patterns of groundwater flow identified at the site during that same period of record.

TABLE 1.2 Analytical results for volatile organic compounds in groundwater samples collected at Centralia, August 2004 to March 2007.

Well	Screen Interval (ft BGL)	Sample Date	Concentration (µg/L) Carbon Tetrachloride	Chloroform	Methylene Chloride
MW01	54.5–64.5	8/24/04	ND[a]	ND	ND
		9/10/05	ND	ND	ND
		10/11/05	ND	ND	ND
		3/15/06	ND	ND	ND
		9/25/06	ND	ND	ND
		3/29/07	ND	ND	ND
MW02	49.5–59.5	8/26/04	215	6.2	ND
		9/11/05	776	33	ND
		10/12/05	528	21	ND
		3/16/06	847	21	ND
		9/26/06	1233	25	ND
		3/26/07	829	14	ND
MW03	50.5–60.5	8/24/04	1.2	ND	ND
		9/10/05	1.6	ND	ND
		10/11/05	1.8	ND	ND
		3/17/06	2.6	0.2 J[b]	ND
		9/26/06	2.7	ND	ND
		3/27/07	2.5	ND	ND
MW04	37.5–47.5	8/24/04	ND	ND	ND
		9/11/05	0.9 J	ND	ND
		10/11/05	0.8 J	ND	ND
		3/15/06	1.3	ND	ND
		9/25/06	1.4	0.1 J	ND
		3/28/07	2.1	ND	ND
MW05	34.5–44.5	8/25/04	ND	ND	ND
		9/10/05	1.9	ND	ND
		10/11/05	1.5	ND	ND
		3/15/06	1.3	ND	ND
		9/25/06	1.3	ND	ND
		3/28/07	0.5 J	ND	ND

TABLE 1.2 (Cont.)

			Concentration (µg/L)		
Well	Screen Interval (ft BGL)	Sample Date	Carbon Tetrachloride	Chloroform	Methylene Chloride
MW06	46.5–56.5	8/25/04	ND	ND	ND
		9/10/05	ND	ND	ND
		10/11/05	0.3 J	ND	ND
		3/15/06	0.2 J	ND	ND
		9/27/06	ND	ND	ND
		3/27/07	ND	ND	ND
MW07	45–55	3/14/06	0.4 J	0.6 J	ND
		9/26/06	1.1	ND	ND
		3/26/07	1.8	ND	ND
MW08	38–53	3/14/06	ND	ND	ND
		9/26/06	ND	ND	ND
		3/27/07	ND	ND	ND
MW09	25–35	3/15/06	ND	ND	ND
		9/25/06	ND	ND	ND
		3/27/07	ND	ND	ND
MW10	30–45	3/14/06	ND	ND	ND
		9/26/06	ND	ND	ND
		3/28/07	ND	ND	ND
SB01	40–50	8/26/04	186	6.5	ND
		9/9/05	269	6.8	ND
		10/12/05	288	6.6	ND
		3/17/06	320	5.7	ND
		9/27/06	267	6.3	ND
		3/27/07	222	4.9	ND
SB04	51–61	8/26/04	30	ND	ND
		9/9/05	47	0.6 J	ND
		10/12/05	44	0.5 J	ND
		3/16/06	51	0.5 J	0.4 J B[c]
		9/25/06	54	0.7 J	ND
		3/28/07	44	0.5 J	ND

TABLE 1.2 (Cont.)

Well	Screen Interval (ft BGL)	Sample Date	Concentration (μg/L)		
			Carbon Tetrachloride	Chloroform	Methylene Chloride
SB05	32–42	8/26/04	59	5.5	ND
		9/9/05	77	7.2	ND
		10/12/05	54	5.5	ND
		3/17/06	104	7.2	ND
		9/27/06	139	12	ND
		3/28/07	138	12	ND
SB07R	45–60	3/15/06	41	2.7	ND
		9/26/06	30	1.7	ND
		3/26/07	30	1.7	ND
SB08	52–62	8/26/04	79	3.1	ND
		9/8/05	80	2.6	ND
		10/12/05	77	2.8	ND
		3/17/06	91	2.7	ND
		9/21/06	53	1.6	ND
		3/28/07	64	2.0	ND
SB09	32–42	8/26/04	ND	ND	ND
		9/11/05	ND	ND	ND
		10/11/05	ND	ND	ND
		3/17/06	ND	ND	ND
		9/25/06	ND	ND	ND
		3/28/07	ND	ND	ND

[a] ND, not detected at an instrument detection limit of 0.1 μg/L.

[b] Qualifier J indicates an estimated concentration below the method quantitation limit of 1.0 μg/L.

[c] Qualifier B indicates that the contaminant was present in the associated method blank.

TABLE 1.3 Scoring of biodegradation processes at Centralia — March 2007 data.[a]

		MW01		MW02		MW03		MW04		MW05		MW06		MW07		MW08	
Constituent	Units	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points	Conc.	Points
Dissolved Oxygen	mg/L	4.39	0	2.29	0	7.73	-3	5.46	-3	4.53	0	0.11	3	1.87	0	1.49	0
Nitrate	mg/L	0.23	2	9	0	9.7	0	2.6	0	2	0	0.044	2	0.71	2	3.2	0
Iron(II)	mg/L	0	0	NR[c]	–	NR	–	0	0	0	0	0	0	0	0	0.21	0
Sulfate	mg/L	5	2	15	2	7.6	2	5.1	2	3	2	5.2	2	20	0	11	2
Sulfide	mg/L	< 0.02	0	< 0.02	0	< 0.02	0	0.027	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0
Methane	mg/L	< 0.002	0	0.021	0	< 0.002	0	0.0062	0	< 0.002	0	0.0065	0	< 0.002	0	< 0.002	0
ORP	mV	174	0	67	0	268	0	197	0	295	0	13	1	261	0	237	0
pH	–	6.54	0	6.39	0	6.4	0	6.47	0	6.44	0	6.42	0	6.5	0	6.31	0
Total Organic Carbon	mg/L	< 1	0	1.1	0	< 1	0	< 1	0	< 1	0	4	0	1	0	1.9	0
Temperature	^{o}C	16.5	0	15.7	0	15.3	0	15.4	0	14.4	0	19	0	15.8	0	15.8	0
Carbon Dioxide[b]	mg/L	NR	–	50	0	25	0	NR	–	35	0	20	0	30	0	30	0
Alkalinity[b]	mg/L	310	0	360	0	370	0	360	0	320	0	330	0	350	0	390	0
Chloride[b]	mg/L	11	0	8.2	0	22	0	11	0	5.2	0	8.4	0	5.9	0	34	2
Dissolved Hydrogen	nM	NA[d]	–	3.1[e]	3	NA	–	NA	–	NA	–	NA	–	NA	–	NA	–
Chloroform	μg/L	< 1	0	14	2	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0
Dichloromethane (methylene chloride)	μg/L	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0
	Total points =>		4		7		-1		-1		2		8		2		4

TABLE 1.3 (Cont.)

Constituent	Units	MW09 Conc.	MW09 Points	MW10 Conc.	MW10 Points	SB01 Conc.	SB01 Points	SB04 Conc.	SB04 Points	SB05 Conc.	SB05 Points	SB07R Conc.	SB07R Points	SB08 Conc.	SB08 Points	SB09 Conc.	SB09 Points
Dissolved Oxygen	mg/L	4.1	0	5.09	-3	3.81	0	6.18	-3	2.58	0	5.08	-3	3.57	0	0.89	3
Nitrate	mg/L	3.8	0	1.1	0	0.8	2	4.6	0	2.1	0	1.1	0	0.68	2	1.2	0
Iron(II)	mg/L	0.69	0	0	0	0.23	0	0.23	0	0.07	0	0.07	0	0.24	0	0.09	0
Sulfate	mg/L	6.4	2	9.1	2	7.4	2	15	2	4.9	2	11	2	7.4	2	32	0
Sulfide	mg/L	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0	< 0.02	0
Methane	mg/L	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0	< 0.002	0
ORP	mV	152	0	270	0	173	0	266	0	296	0	237	0	208	0	236	0
pH	–	6.35	0	6.36	0	6.37	0	6.45	0	4.03	-2	6.38	0	6.53	0	6.32	0
Total Organic Carbon	mg/L	< 1	0	1.2	0	< 1	0	2	0	1.2	0	1.1	0	< 1	0	1.5	0
Temperature	^oC	14.9	0	17	0	18	0	16.2	0	16.7	0	19	0	15.8	0	14.3	0
Carbon Dioxide[b]	mg/L	30	0	35	0	25	0	NR	–	35	0	40	0	35	0	40	0
Alkalinity[b]	mg/L	360	0	330	0	340	0	370	0	320	0	310	0	330	0	530	0
Chloride[b]	mg/L	6.9	0	100	2	30	2	48	2	66	2	23	2	17	0	16	0
Dissolved Hydrogen	nM	NA	–	NA	–	71[e]	3	24[e]	3	11[e]	3	NA	–	6.1[e]	3	NA	–
Chloroform	μg/L	< 1	0	< 1	0	4.9	2	0.5 J[f]	2	12	2	1.7	2	2	2	< 1	0
Dichloromethane (methylene chloride)	μg/L	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0	< 1	0
	Total points =>		2		1		11		6		7		3		9		3

[a] Scoring is based on results for samples collected in March 2007. Points are interpreted as follows (EPA 1998):
0–5 Inadequate evidence for reductive dechlorination.
6–14 Limited evidence for reductive dechlorination.
15–20 Adequate evidence for reductive dechlorination.
> 20 Strong evidence for reductive dechlorination.

[b] For evaluation of alkalinity, carbon dioxide, and chloride, MW01 (because of its location) was selected to represent background levels. For these constituents, points are awarded when the concentration is greater than twice the background concentration.

[c] NR, not recorded.

[d] NA, not analyzed for dissolved hydrogen in March 2007.

[e] Dissolved hydrogen result from September 2005 sampling.

[f] Qualifier J indicates an estimated concentration below the method quantitation limit of 1.0 μg/L.

1.3 Summary

The results of site characterization and monitoring at the former CCC/USDA facility support the conclusion that MNA, by itself, does not represent the most viable remedial alternative for restoration of the groundwater at Centralia. Although limited evidence has been found that the natural site conditions might promote natural *in situ* reductive dechlorination of carbon tetrachloride at some locations, the effectiveness and areal extent of these processes, as documented to date, have proven insufficient to effectively mitigate the contaminant levels.

The identified groundwater contamination currently poses no unacceptable health risks, in the absence of identified potential human receptors in the vicinity of the former CCC/USDA facility. Carbon tetrachloride contamination identified in subsurface soils at SB12 is at concentrations on the order of the Kansas Tier 2 RBSL of 200 μg/kg for the soil-to-groundwater protection pathway.

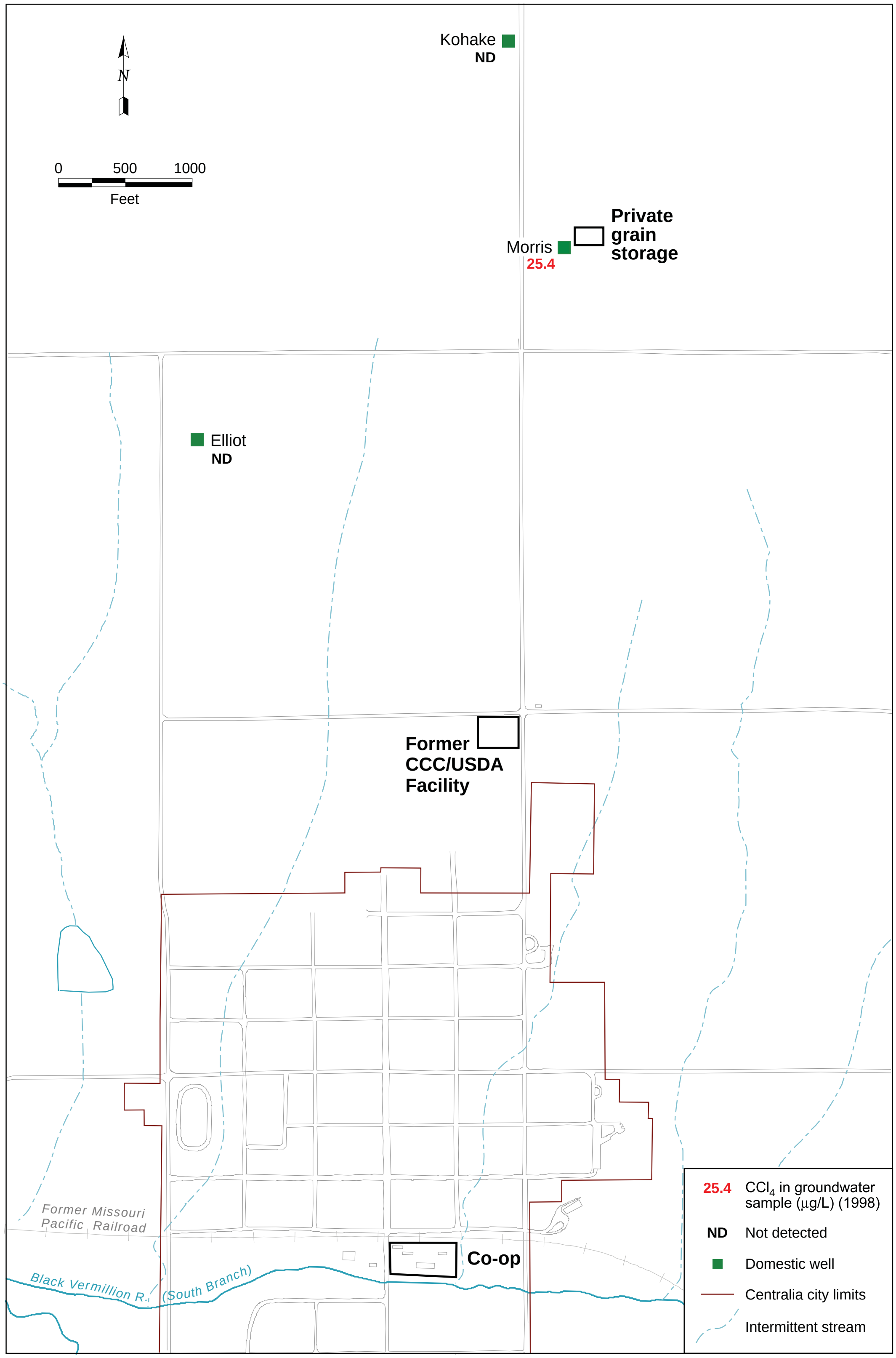

FIGURE 1.1 Locations of the former CCC/USDA facility and the contaminated private well at Centralia.

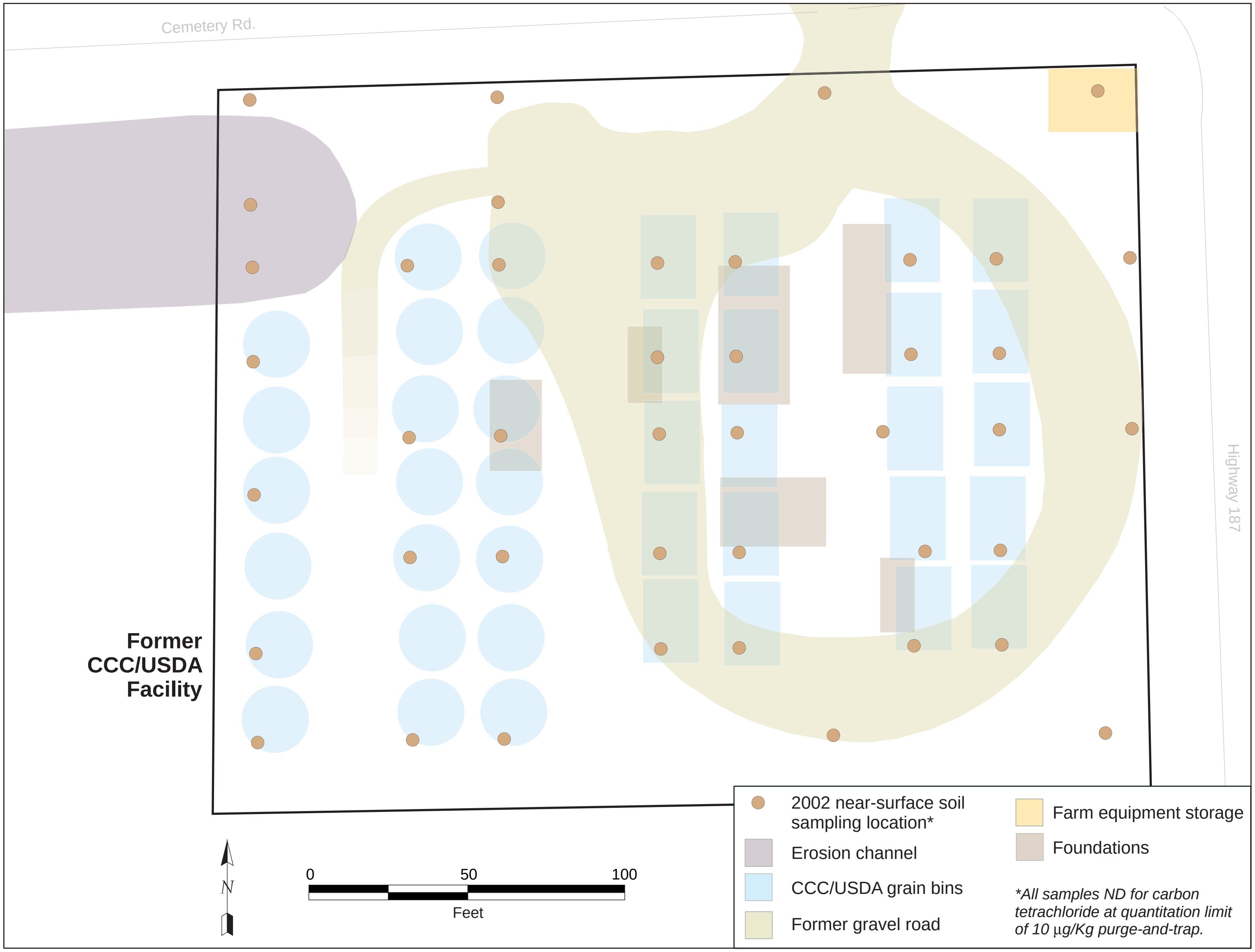

FIGURE 1.2 Locations of near-surface soil sampling in 2002. No carbon tetrachloride was detected.

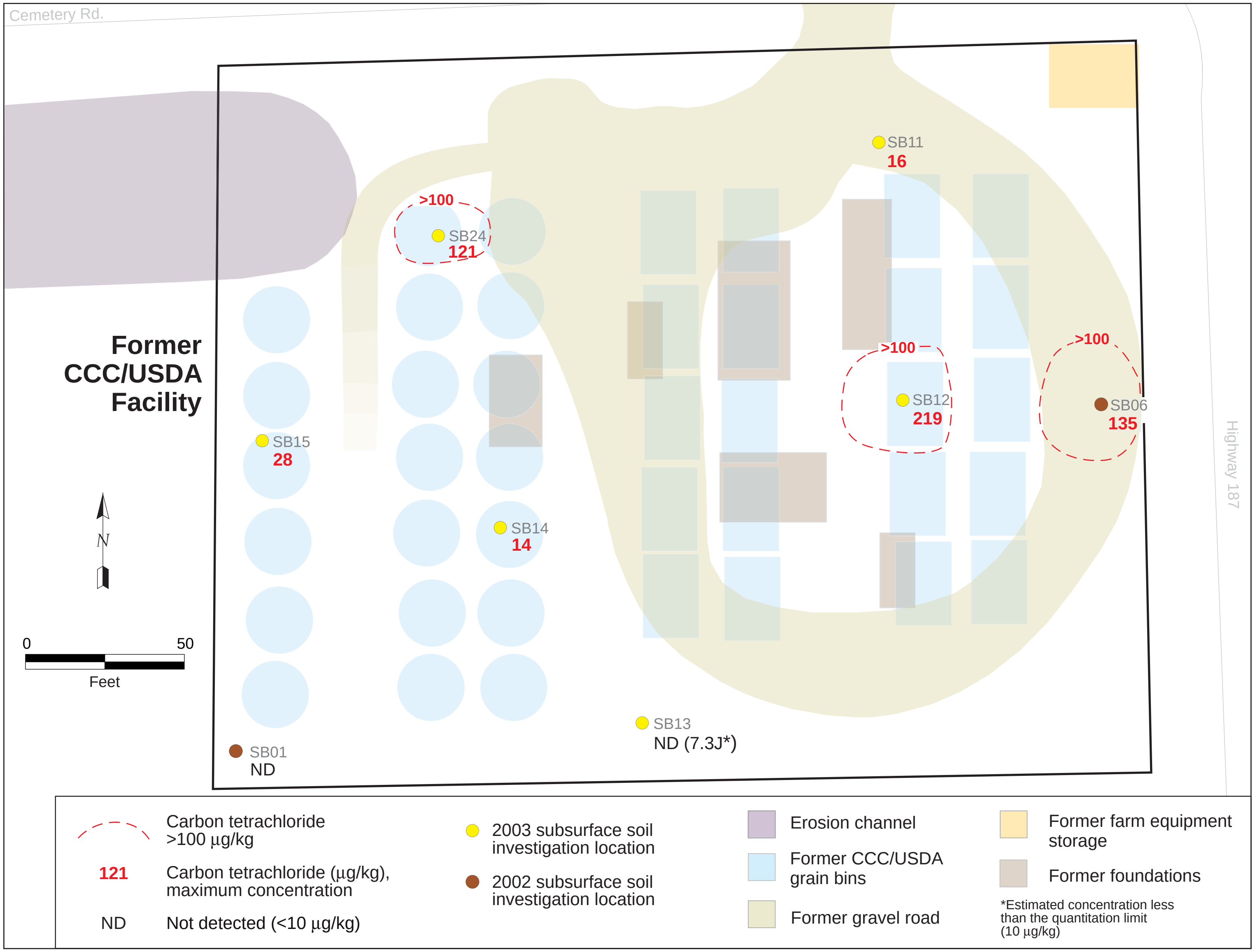

FIGURE 1.3 Locations and results of vertical-profile soil sampling in 2002 and 2003.

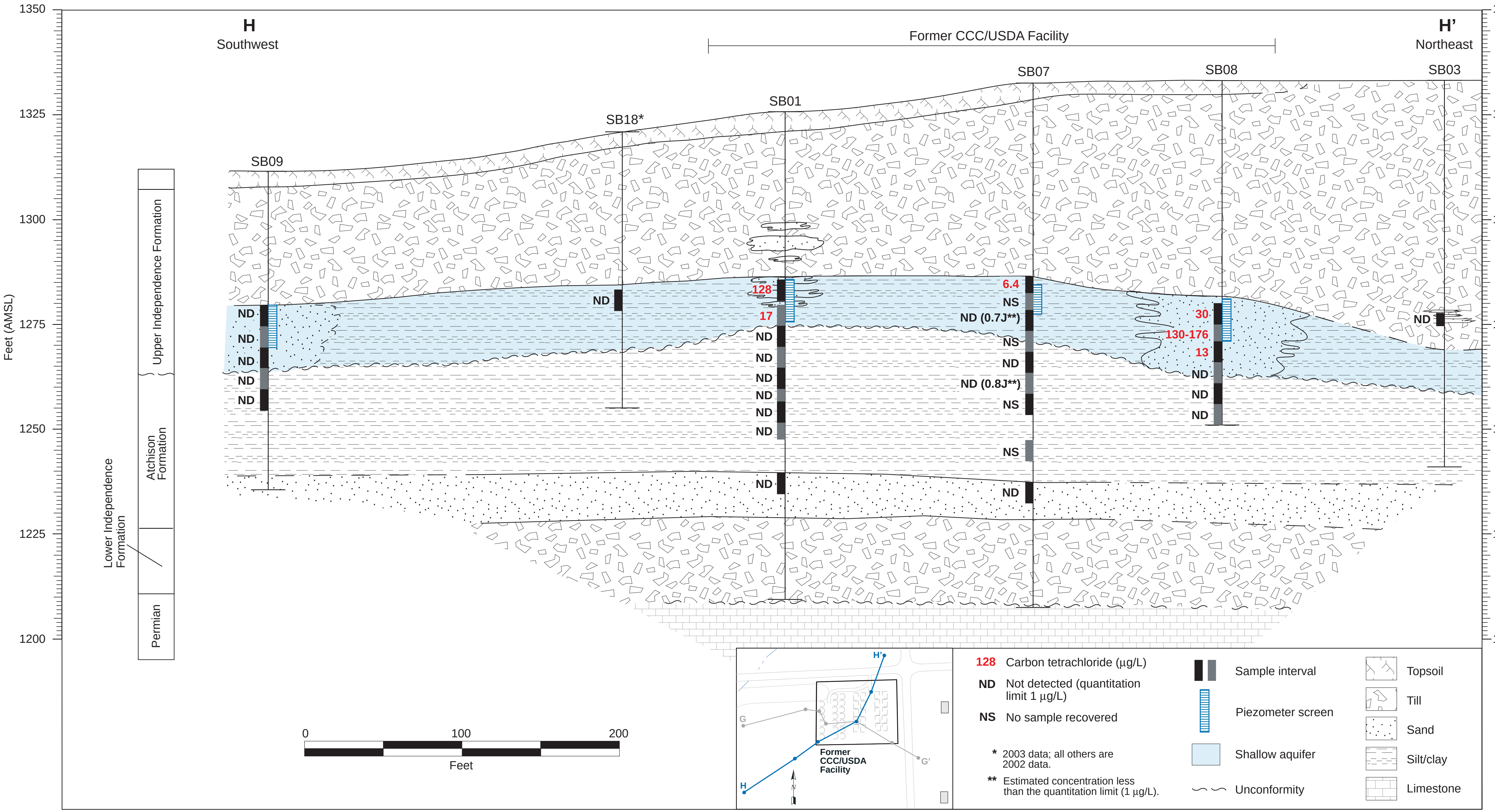

FIGURE 1.4 Southwest-northeast hydrogeologic cross section at Centralia (vertically exaggerated), with results for carbon tetrachloride in vertical-profile groundwater samples collected in 2002 and 2003.

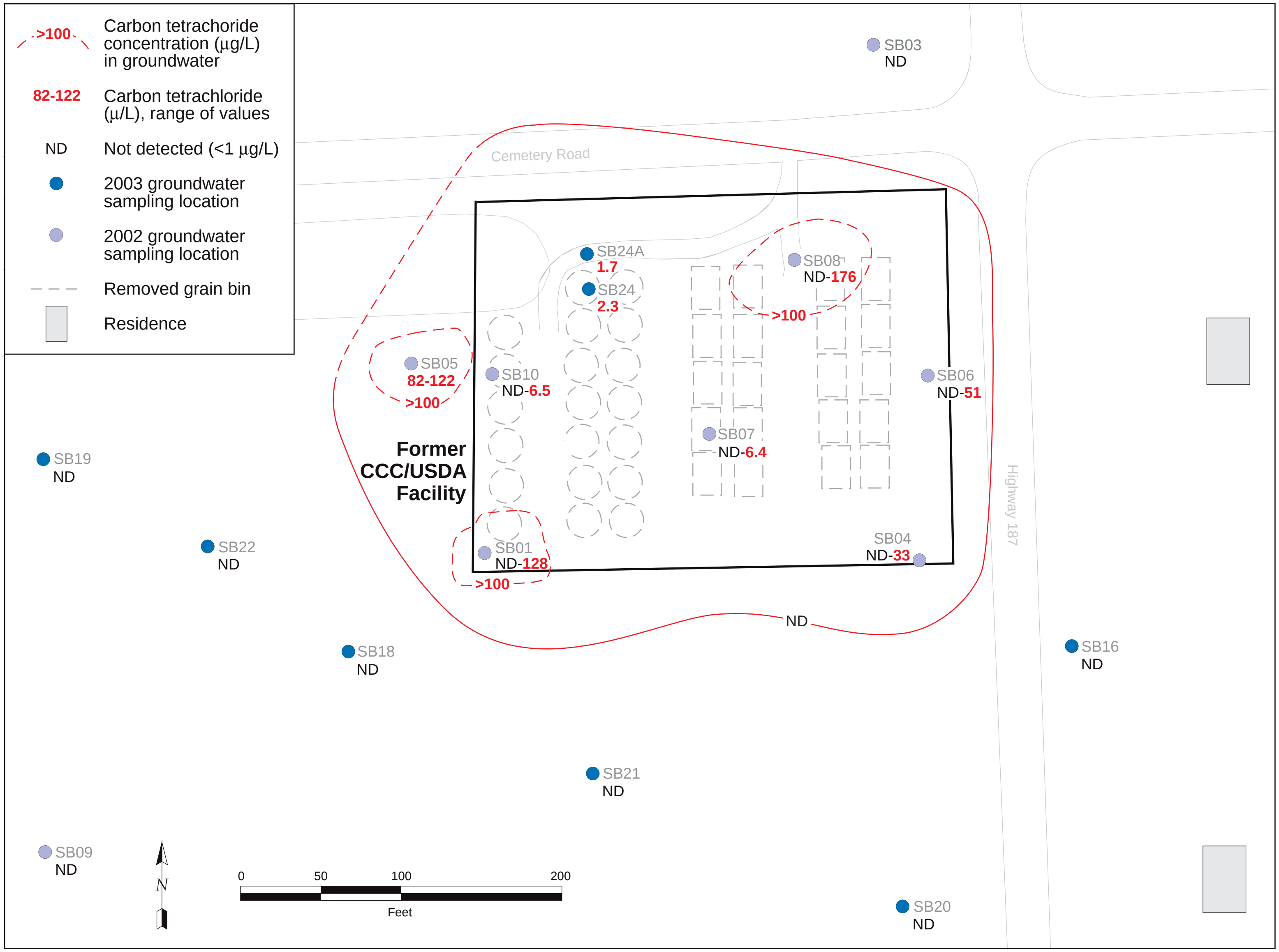

FIGURE 1.5 Lateral distribution of carbon tetrachloride in the shallow aquifer at Centralia, as interpreted from analytical results for 2002 and 2003.

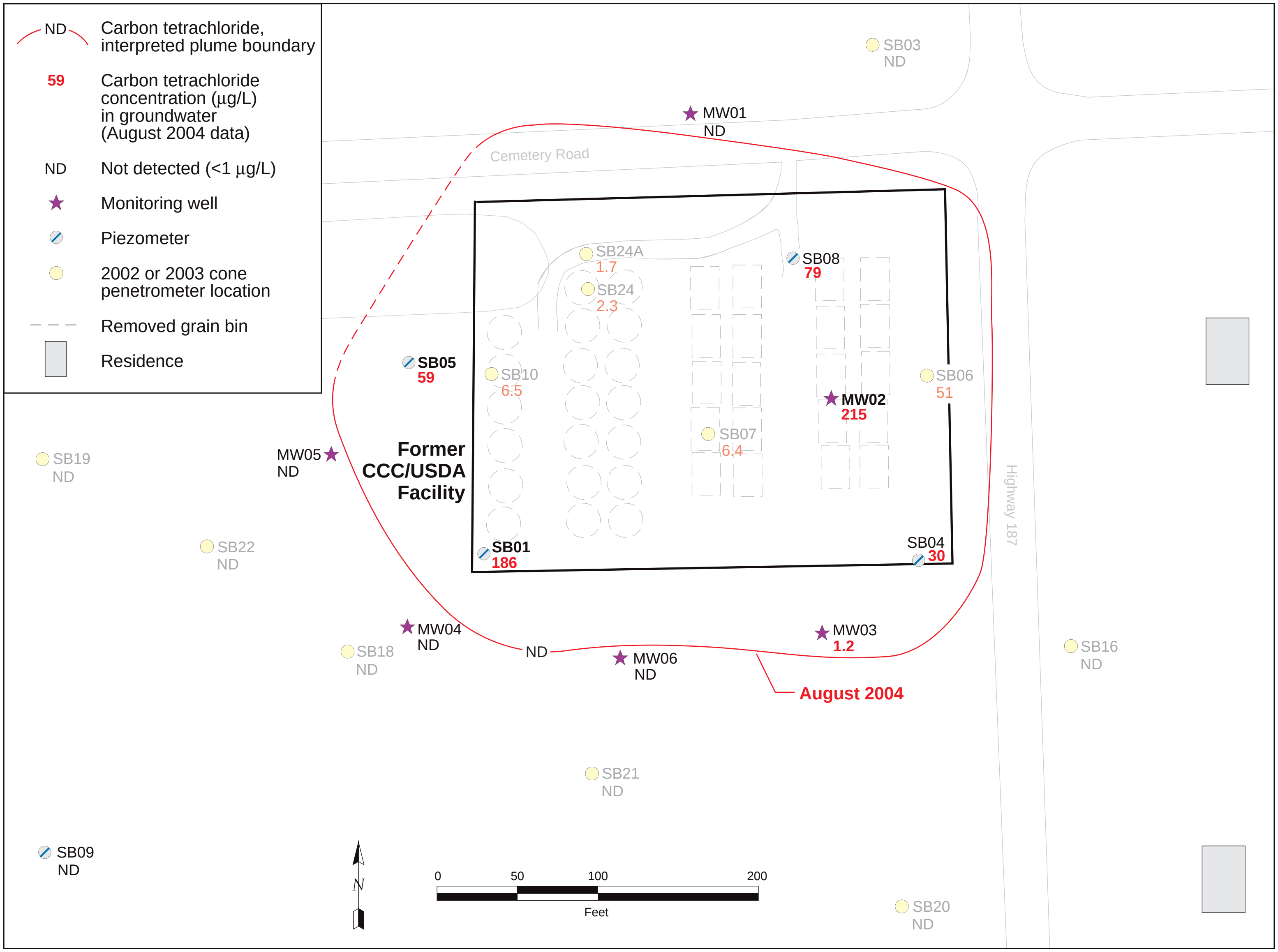

FIGURE 1.6 Monitoring network established in 2004, with the lateral distribution of carbon tetrachloride in the shallow aquifer at Centralia, as interpreted from analytical results for groundwater sampling in August 2004 and earlier.

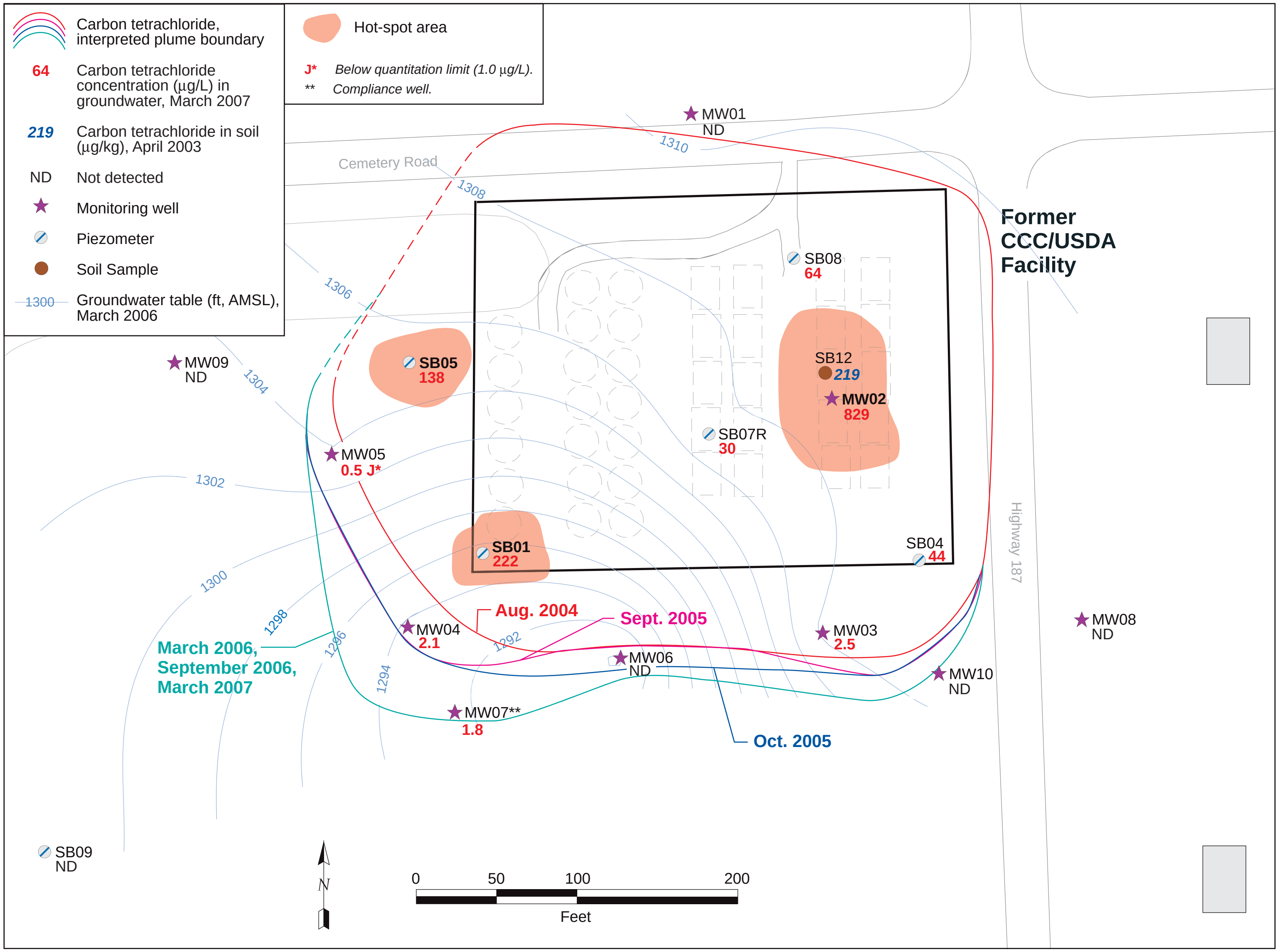

FIGURE 1.7 Analytical results for carbon tetrachloride in groundwater samples collected in March 2007, with interpreted water level contours for March 2006, interpreted plume boundaries in 2004-2007, and analytical results (maximum) for soil samples collected at SB12 in April 2003.

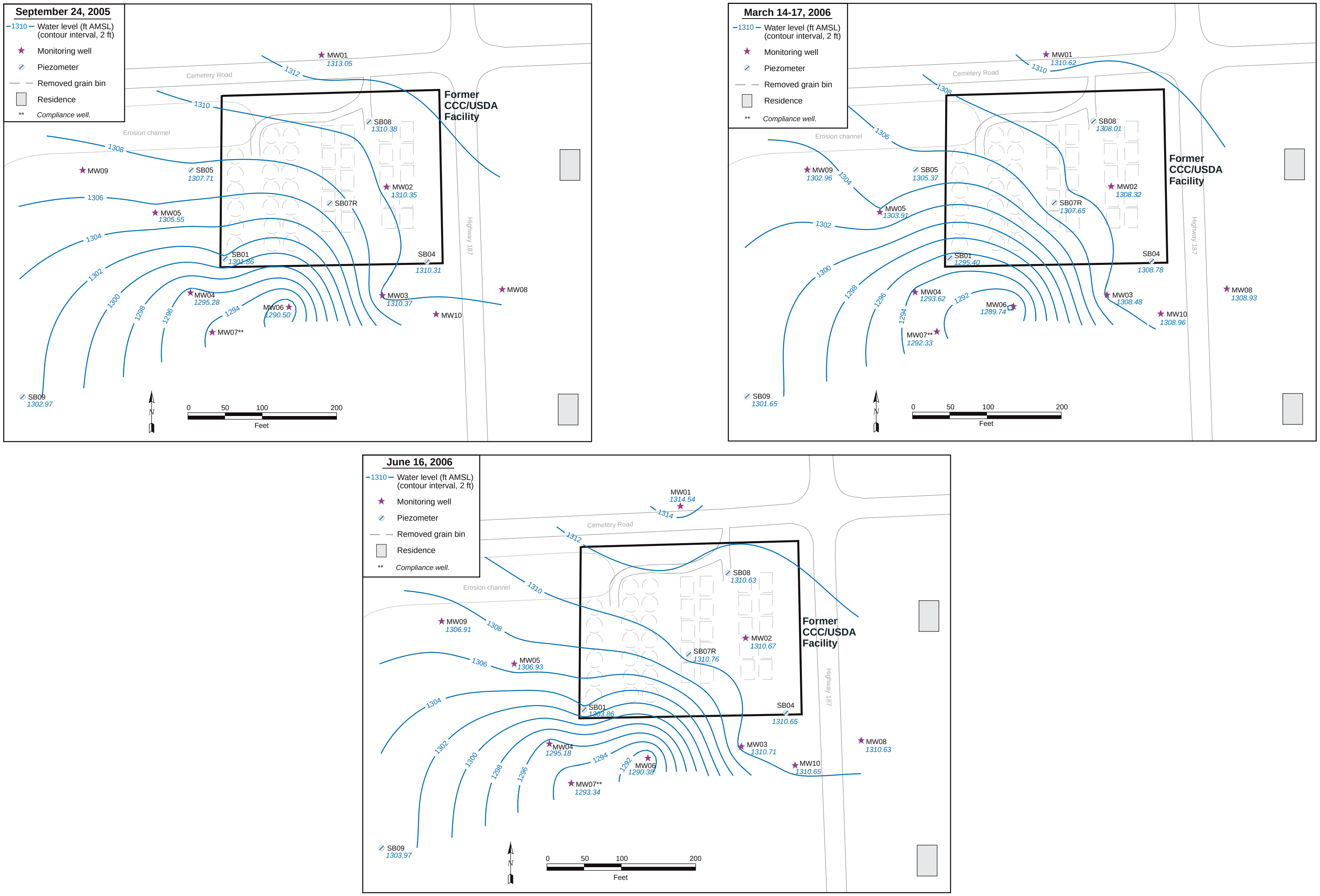

FIGURE 1.8 Water level contours for the shallow aquifer at Centralia on September 24, 2005, March 14-17, 2006, and June 16, 2006, as interpreted from measurements in a monitoring network expanded in January 2006 through the addition of wells MW07-MW10.

2 Description of the Recommended Interim Measure

The CCC/USDA is recommending an initial short-term, field-scale pilot test of a commercially available remedial approach, with subsequent implementation of the approach (if the pilot test is successful) as a non-emergency IM. The purpose is to mitigate existing contaminant levels in soil and groundwater at Centralia and to moderate or decrease the potential future concentrations of carbon tetrachloride in the groundwater. The initial pilot test will address one of three identified hot-spot areas, and the subsequent full implementation will address the other two hot-spot areas.

The EHC material recommended for use in treatment at Centralia is marketed by Adventus Americas, Inc., Freeport, Illinois. The EHC material promotes *in situ* chemical reduction (ISCR) of carbon tetrachloride. In the proposed application of the ISCR approach, the EHC material, which is a proprietary mixture of food-grade organic carbon and zero-valent iron (ZVI), will be introduced into the subsurface and released slowly into the formation. In the saturated and vadose zones, the EHC material will create highly reducing conditions that will foster both chemical and biological reductive dechlorination of carbon tetrachloride. The estimated effective lifetime of the EHC material following injection, on the basis of applications reported by the manufacturer, is 1-5 yr (Adventus 2006, 2007a-e).

The CCC/USDA recommends the initial pilot testing of the ISCR approach to address the elevated carbon tetrachloride levels identified in the hot-spot area at MW02, as well as the possible continuing soil source identified nearby, at SB12 (Figure 2.1). A three-dimensional grid pattern of direct-push injection points will be used to distribute the EHC material (in slurry or aqueous form) throughout the volume of contaminated aquifer material in this area, as well as in the vadose zone at selected locations. Injection of the EHC material will be conducted by a licensed contractor (to be identified upon approval of this conceptual design by the KDHE), under the supervision of Adventus and Argonne technical personnel.

Argonne will periodically sample a network of temporary and permanent borings to be installed in the injection area. The purpose will be to document (1) the contaminant distribution in the saturated and vadose zones prior to injection, (2) the distribution of the EHC material in these zones immediately following injection and at intervals thereafter, and (3) the changes in contaminant concentrations occurring over time in response to the imposed treatment. The details are discussed in Section 4.

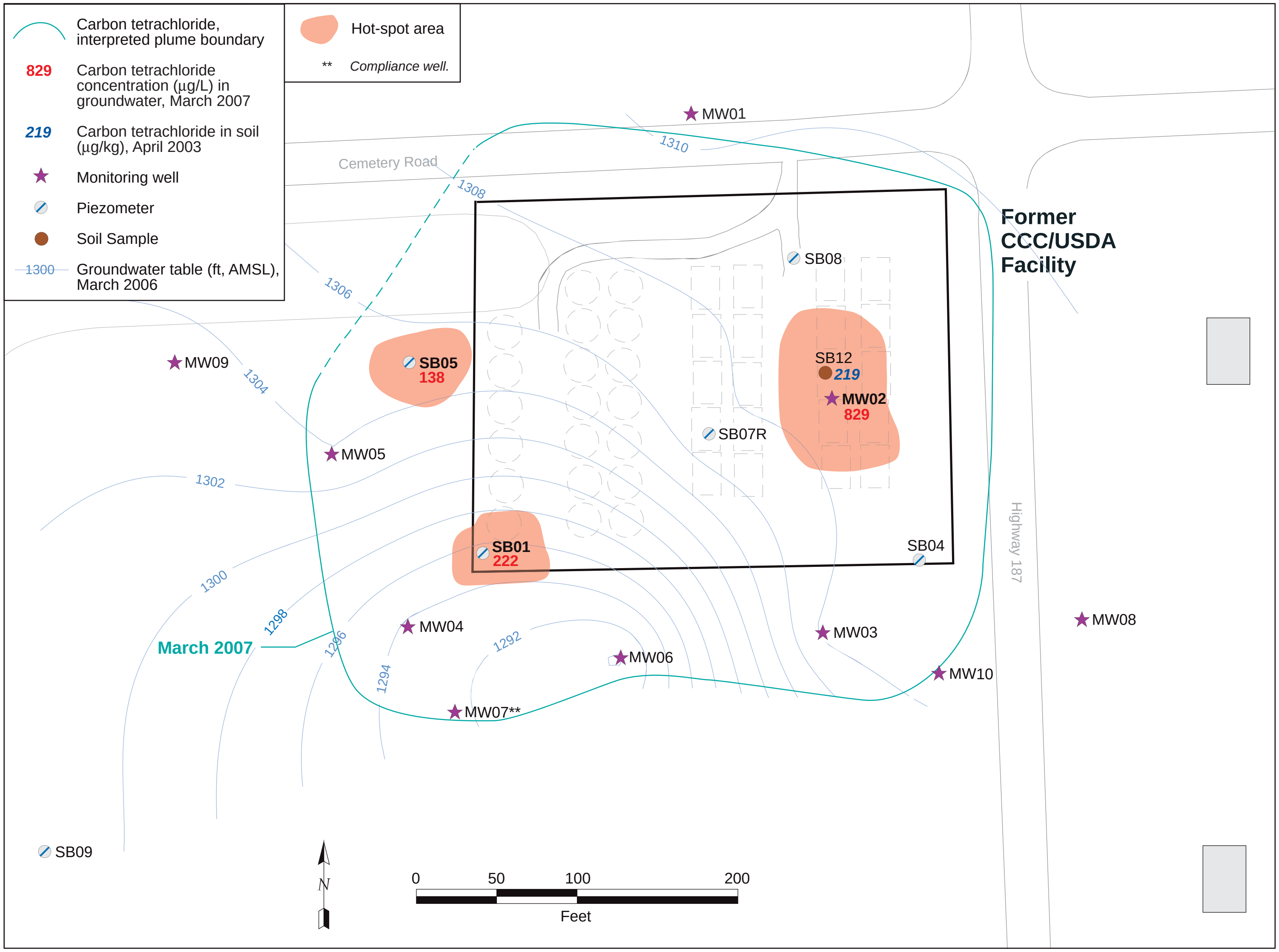

FIGURE 2.1 Analytical results for carbon tetrachloride in groundwater samples collected in the hot-spot areas in March 2007, with interpreted water level contours for March 2006, the interpreted plume boundary in March 2007, and the analytical results (maximum) for carbon tetrachloride in soil at location SB12 in April 2003.

3 Interim Remedial Measure Objectives

The regulatory, technical, and logistic objectives of the proposed non-emergency IM are as follows:

- To reduce the existing concentrations of carbon tetrachloride in groundwater in the three identified hot-spot areas to levels that are acceptable to the KDHE.

- To reduce carbon tetrachloride concentrations in the soils near the location of former soil boring SB12 and existing monitoring well MW02 to levels below the KDHE Tier 2 RBSL (200 µg/kg) for this contaminant.

- To address the above two objectives in a cost- and time-effective manner, by employing an approach that will limit potential disruption of the contaminated private property at Centralia and will limit or eliminate the potential generation, handling, and required disposal of contaminated investigation-derived wastes.

- To operationally test and critically evaluate the viability of the ISCR approach, specifically the Adventus EHC material, as a remedial technology for restoration of the subsurface soils and groundwater at Centralia, as well as potentially at other former CCC/USDA investigation sites in Kansas that might have similar hydrogeologic characteristics, geochemical features, and remedial requirements.

- To gain practical technical and logistic experience in implementation of the ISCR approach and thus facilitate the development of optimal methods and techniques for the potential application of this approach at Centralia and other CCC/USDA investigation sites where the approach might be applicable.

4 Interim Measure Design

Argonne's investigations have shown that the lithologic properties of the unit hosting the contaminated aquifer at Centralia vary both vertically and laterally, resulting in a heterogeneous permeability distribution and relatively restricted groundwater movement across much of the site. An initial short-term, field-scale pilot test is recommended at the most contaminated of the three identified hot-spot areas, near MW02 (Figure 2.1). The pilot test will (1) determine the operational techniques required for optimal implementation and monitoring of the ISCR approach and (2) verify the suitability of this approach for treatment of the carbon tetrachloride contamination at the Centralia site.

The design basis, design specifications, and proposed monitoring activities are outlined below. Estimated costs and a working schedule for implementation of the recommended pilot study will be submitted in an engineering design document upon KDHE approval for use of the ISCR approach at Centralia.

The results of monitoring in the pilot test area over a recommended period of three months following injection of the EHC material will be presented for review by the CCC/USDA and KDHE project managers. If the CCC/USDA and KDHE concur that the ISCR approach has met the objectives specified in Section 3 for the pilot test, the CCC/USDA will request KDHE authorization for the use of this approach in the other two identified hot-spot areas (near SB01 and SB05).

Detailed design and scheduling information for full implementation of the IM near SB01 and SB05 will be developed when the results for the pilot study near MW02 become available. Upon KDHE authorization for use of the ISCR approach as the IM remedy at Centralia, the detailed information will be incorporated into the engineering design for the full implementation. The engineering design will then be submitted for KDHE review and approval.

4.1 Design Basis

Although ISCR is considered a new, emerging remedial approach, the Adventus EHC product has been demonstrated to be effective in the treatment of carbon tetrachloride contamination in groundwater (Adventus 2007a-c) and has been employed at a carbon tetrachloride contamination site elsewhere in Kansas (Cargill Flour Mill and Elevator, Wellington, Kansas; Adventus 2007d) with the approval of the KDHE (2007b).

At the request of the CCC/USDA, Argonne conducted preliminary bench-scale treatability tests of the Adventus EHC and EHC-M remediation products, in conjunction with pure laboratory reagents and also with soil and groundwater samples obtained from the Centralia area, to which known quantities of carbon tetrachloride had been added. (EHC-M is a variant of the EHC material that is specially formulated for the treatment of heavy metals. Though the potential use of EHC-M is not warranted at the Centralia site, the material was included in Argonne's preliminary batch testing for comparison with the standard EHC product.) The results of these preliminary experiments are in Appendix B. In the presence of either Adventus product, the laboratory batch tests demonstrated a reduction of more than 90% in the concentration of carbon tetrachloride in the Centralia samples with the compound added in known quantities.

The EHC products are designed to promote the degradation of carbon tetrachloride (and other chlorinated hydrocarbons) through the combined action of both direct inorganic processes and biologically mediated processes, under highly reducing conditions (with very low oxidation-reduction potential [ORP]). The organic component of the EHC material is hydrophilic and rich in nutrients. In combination with a high surface area, these properties promote the growth of bacteria in the subsurface. As the bacteria grow, indigenous heterotrophic species deplete the available dissolved oxygen, thereby reducing the local ORP. As the bacteria grow, they also ferment carbon and release volatile fatty acids that diffuse from the fermentation site into the contaminated aquifer and provide electron donors for other bacteria, including dehalogenators and halorespiring species. The small ZVI particles in the EHC material provide a large reactive surface area, which promotes abiotic dechlorination and causes a further drop in ORP in the formation due to chemical oxygen scavenging.

Adventus (2007b) reports that ORP values as low as -550 mV can be achieved in the contaminated formation after the injection of EHC material. Under these conditions, many normally recalcitrant organic compounds (including carbon tetrachloride) can become thermodynamically unstable and be degraded via pathways that produce few, if any, undesirable intermediate degradation products.

The investigations conducted by Argonne on behalf of the CCC/USDA have demonstrated that the natural conditions in the shallow aquifer at Centralia are, at least locally, conducive to the reductive dechlorination of carbon tetrachloride. The proposed ISCR treatment approach is therefore expected to enhance the degradative processes that are already occurring (to a limited degree) at this site. Argonne's studies have also shown that the rates of groundwater and contaminant migration in the aquifer are relatively slow. Hence, substantial residence time is expected for the contaminants and the injected amendments in the aquifer volumes targeted at MW02 for treatment during the pilot test, as well as in the hot-spot areas at SB01 and SB05 identified for full implementation of this IM.

4.2 Design Specifications

The design of the proposed Centralia pilot test program summarized below was developed as a collaborative effort involving scientific and technical staff of the CCC/USDA; Argonne; Adventus Americas, Inc.; and prospective implementation contractors. The design is based on the analytical data and the geologic, hydrogeologic, and geochemical interpretations summarized in this document. The design is intended to meet the program objectives identified in Section 3.

4.2.1 Pilot Test Treatment Area

The area selected for the short-term field-scale pilot test is approximately centered on the locations of existing monitoring well MW02 and former investigative boring SB12 (Figure 4.1) These two borings penetrated the highest concentrations of carbon tetrachloride identified in both vadose zone soils and groundwater at the Centralia investigation site. The two borings define a hot-spot area that has demonstrated sustained high levels of the contaminant. The pilot test activities will be confined to a rectangular area around MW02 and SB12. The surface of the rectangular area will measure approximately 45 ft wide by 75 ft long, oriented approximately orthogonally to the apparent direction of groundwater flow in this portion of the site. The targeted area is currently privately owned, uncultivated pastureland. The CCC/USDA has obtained access to this property for sampling in the past and foresees no problems in obtaining access for the proposed pilot study.

4.2.2 Strategy for Injection of the ISCR Amendments

4.2.2.1 Distribution of Injection Points and Injection Operations

An arrangement of 15 temporary injection points in a grid pattern is proposed (Figure 4.2) for emplacement of the ISCR amendments (EHC material). The injection points will be arranged initially in a uniform spacing of 15 ft, yielding an anticipated injection radius of influence of 7.5 ft per injection point. The recommended spacing is based on experience of Adventus personnel and the prospective contractors with injection of the EHC material at other investigation sites having roughly comparable subsurface characteristics. As the injection of EHC material progresses at Centralia, this spacing might be modified, if necessary (subject to the approval of the CCC/USDA and KDHE project managers), to ensure that an adequate distribution of material in the targeted testing volume is achieved.

The contractor will accomplish the injection by using direct-push equipment (Geoprobe or equivalent) that has been specially modified by the contractor to permit the emplacement of EHC material over carefully controlled depths in the subsurface. Injection of the EHC material will be performed over successive depth intervals at each boring location. The exact depth intervals will be determined in consultation with Adventus and contractor personnel and with the CCC/USDA and KDHE project managers. Injection into the saturated zone is proposed over an approximate depth interval of 20 ft at each injection point, from 40 ft to 60 ft below ground level (BGL). Because carbon tetrachloride contamination of vadose zone soils was previously identified only at the SB12 investigative boring location, EHC injection into the vadose zone is recommend at the ten injection points closest to this location. At these points, injection into the vadose zone soils will extend over the 20-ft depth interval from 20 ft to 40 ft BGL.

Additional descriptions of the equipment and details of the procedures to be used during injection of the EHC material will be provided in the engineering design for the pilot test, along with a detailed heath and safety plan for the injection component of the pilot test. The health and safety plan (to be submitted by the contractor) will meet Argonne standards and will be approved by Argonne.

4.2.2.2 Selection and Preparation of the EHC Material

The pilot study's targeted volume *in the saturated zone* (approximately 67,500 ft^3) will be treated with the standard EHC material (Adventus 2007a,b), which is supplied in a solid, dry powder form. The EHC material will be mixed on-site immediately prior to subsurface emplacement, with uncontaminated (by carbon tetrachloride) water from the Centralia municipal supply system, to form an injection slurry containing approximately 30% solids by weight. Slurry will be injected uniformly at each location, if possible, to yield an approximate concentration of EHC in the amended groundwater of 0.4 lb/ft^3, or 0.1% (mass of EHC to total mass of saturated soil treated).

The pilot test's targeted volume (approximately 18,000 ft^3) of *contaminated vadose zone soil* will be treated with an aqueous formulation of EHC, known as EHC-A (Adventus 2006, 2007a,d,e,f). EHC-A is composed of a water-soluble organic amendment and soluble reduced iron (Fe^{2+}). The aqueous form of EHC is recommended for effective distribution of injected material in vadose zone soil of limited permeability. The EHC-A will be injected as a relatively dilute solution (10% EHC by weight), thus increasing the volume of injection fluid required to achieve a final EHC concentration of 0.1% (by mass, relative to the total mass of soil) in the treated interval. EHC-A, which (like the standard EHC material) is also supplied as a dry powder, will be mixed on-site immediately prior to subsurface emplacement, with uncontaminated (by carbon tetrachloride) water from the Centralia municipal supply system.

Material safety data sheets for the EHC and EHC-A products are in Appendix C.

4.2.3 Pilot Test Monitoring Program

A detailed program of vadose zone soil and groundwater sampling and analyses will be performed by Argonne as part of the Centralia pilot study. The results will permit documentation of the ISCR treatment approach, as well as the operational procedures and techniques used to conduct the pilot investigation. The results will serve as the basis for critical evaluation of the effectiveness of the ISCR approach.

The primary elements of the evaluation program will be as follows:

- Pre-treatment baseline characterization

- Evaluation of the injection process and the initial distribution of the EHC material

- Post-injection monitoring

The specific activities and analyses to be conducted during each phase of the performance monitoring program are summarized below and in Table 4.1. The locations of the monitoring activities are shown in Figure 4.3.

All of the sample collection, sample analysis, and piezometer installation activities described in this section will be performed in accord with the detailed methodologies and procedures in the KDHE-approved *Master Work Plan* for environmental investigations in Kansas (Argonne 2002b).

4.2.3.1 Pre-treatment Baseline Characterization

To determine the vertical and areal distribution of carbon tetrachloride contamination in the vadose zone soils and in the saturated zone of the pilot test area prior to the application of the ISCR amendments, the Argonne cone penetrometer (CPT) vehicle will be used for baseline soil and groundwater sampling at the pilot test site *before treatment begins* (Table 4.1 and Figure 4.3). The activities will be as follows:

- At four locations in the test area, the instrumented electronic CPT cone will be used to acquire continuous geomechanical measurements of tip pressure, sleeve friction, conductivity (if possible), borehole inclination, and tip-vs.-sleeve ratio to a depth of approximately 60 ft BGL (the base of the targeted treatment interval). Vertical-profile groundwater samples will then be collected at 4-ft intervals through the saturated portion of the planned treatment zone (approximately 40-60 ft BGL) at each of the four boring locations.

- At one investigative boring, sited at the approximate location of previous Argonne boring SB12, sediment core samples will be collected at 4-ft intervals through the anticipated vadose zone treatment interval (approximately 20-40 ft BGL).

- The CPT will be used to select zones to be targeted for piezometer installation after injection of the EHC material (Section 4.2.3.2). The targeted intervals will be sampled through the CPT rods by using a temporary casing and screen.

- The investigative borings will be grouted before EHC injection begins.

- Groundwater samples will be collected from existing permanent monitoring points SB04, SB07R, SB08, and MW03 near the pilot test area, as well as from MW02 in the treatment area.

All of the groundwater samples and sediment core samples outlined above will be submitted for laboratory analyses for VOCs. Selected additional parameters for all groundwater samples, potentially including temperature, conductivity, pH, ORP, dissolved oxygen content, and reduced iron (Fe^{2+}) content, will be determined in the field in accord with procedures in the *Master Work Plan* (Argonne 2002b).

4.2.3.2 Evaluation of the Injection Process and the Initial EHC Distribution

To investigate the effectiveness of the EHC injection process and the resulting distribution of EHC material in the vadose zone soils and in the saturated zone, the following sampling and analyses will be performed *during and immediately after the subsurface injection is complete* (Table 4.1 and Figure 4.3):

- Close monitoring of groundwater in MW02 will be conducted during injection through the measurement of the water level, conductivity, and other parameters.

TABLE 4.1 Summary of proposed monitoring activities for the recommended Interim Measure pilot test at Centralia.

Locations (Symbols in Figure 4.3)	Activity (Analyses)	Subsurface Interval Targeted for Investigation	Frequency
Pre-treatment Baseline			
3 temporary borings (blue ○)	CPT electronics	Surface to ~ 60 ft BGL[b]	Once, prior to EHC injection
	Vertical-profile groundwater (GW)[a] sampling (VOCs)	40-60 ft BGL; sampling at 4-ft intervals	
1 temporary boring near SB12 (brown/blue ○)	CPT electronics	Surface to ~ 60 ft BGL	
	Soil coring (VOCs)	20-40 ft BGL; sampling at 4-ft intervals	
	GW sampling (VOCs)	40-60 ft BGL; sampling at 4-ft intervals	
6 temporary borings (Δ)	GW sampling (VOCs +)[c]	Saturated zone; screen intervals to be determined	
5 existing monitoring points: SB04, SB07R, SB08, MW02, MW03 (★)	GW sampling (VOCs +)	Saturated zone	
Evaluation after Injection			
6 new monitoring points (Δ)	Install piezometers	Saturated zone	Once, immediately after EHC injection
5 existing and 6 new monitoring points (★, Δ)	GW sampling (VOCs +)	Saturated zone	
3 temporary borings at 3 ft, 5 ft, and 7.5 ft from one injection point (locations to be determined)	Soil coring (visual inspection and photography)	20-60 ft BGL, in vadose and saturated zones	
Post-Injection Monitoring			
1 temporary boring near SB12 (brown/blue ○)	Soil coring (VOCs)	20-40 ft BGL; sampling at 4-ft intervals	Once, week 12
			Once, month 12
MW02 and 6 new monitoring points (Δ)	Field parameter measurement	Saturated zone	Weekly, month 1
			Every 2 weeks, months 2-3
			Monthly, months 4-6
			Quarterly, months 7-12
	GW sampling (VOCs) and water level measurement		Every 2 weeks, month 1
			Monthly, months 2-6
			Quarterly, months 7-12
SB04, SB07R, SB08, MW03 (★)	GW sampling (VOCs +) and water level measurement	Saturated zone	Monthly, months 1-6
			Quarterly, months 7-12

[a] GW, groundwater.

[b] BGL, below ground level.

[c] VOCs, plus selected additional parameters. These potentially include temperature, conductivity, pH, redox potential, dissolved oxygen, and reduced iron (Fe^{2+}) content.

- The CPT will be used to install three permanent, 1-in.-diameter monitoring points (piezometers) in the treatment area. Two will be installed near the center of the planned injection grid. One of these piezometers will be installed approximately 3 ft from a planned injection point. The second of these piezometers will be installed approximately midway between this injection point and the nearest adjacent injection point. The third piezometer will be installed in the southeast part of the treatment grid, approximately 30 ft from the two piezometers near the center of the grid. The depth interval(s) to be screened in these three piezometers will be selected on the basis of the identified aquifer characteristics at these locations, with the approval of the CCC/USDA and KDHE project managers. Groundwater samples will be collected from the completed piezometers after they are developed, in accord with KDHE requirements.

- The CPT will also be used to install three additional permanent, 1-in.-diameter monitoring points (piezometers) in the area adjacent to the pilot test site. One piezometer will be located approximately 20 ft to the northeast and upgradient of the test site; the remaining piezometers will be installed 20-30 ft downgradient to the southwest and southeast, respectively, of the test area. The depth interval(s) to be screened in these piezometers will be selected on the basis of the identified aquifer characteristics at these locations, with the approval of the CCC/USDA and KDHE project managers. (These three installations adjacent to the pilot test site will bring the total number of newly installed piezometers to five.) Groundwater samples will be collected from the completed piezometers after they are developed, in accord with KDHE requirements.

- The field parameters for groundwater identified in Section 4.2.3.1 will be measured in the full network of 11 monitoring points (6 new piezometers and 5 previously existing points). Groundwater samples will be collected for VOCs analyses if the field parameters suggest that chemical conditions in the injection area have changed significantly.

- The CPT will be used to collect continuous sediment core samples, from a depth of 20 ft to 60 ft BGL, in 3 investigative borings located approximately

3 ft, 5 ft, and 7.5 ft from 1 of the 15 injection points used to place EHC material in both the vadose zone and the saturated zone in the test area. These locations are not shown in Figure 4.3; they will be identified in consultation with the KDHE and CCC/USDA project managers. The samples will be visually inspected and photographed to determine the radial and stratigraphic distribution of EHC material achieved in relation to the injection point (Adventus 2007a,d). Other tests may be performed in the field to investigate the distribution of EHC material further, on the basis of recommendations from the manufacturer and the results of visual inspection.

- Groundwater levels will be measured in the full network of monitoring points.

4.2.3.3 Post-injection Monitoring

Periodic groundwater sampling and more limited vadose zone soil sampling will be performed *after completion of EHC injection*, at the intervals specified below. The results will be used to determine the effectiveness and the areal range of influence of the pilot ISCR application. The activities to be performed in this phase of the monitoring program are as follows (Table 4.1 and Figure 4.3):

- *During the first month* after injection of the EHC material, field parameters for groundwater, including temperature, conductivity, pH, ORP, dissolved oxygen content, and reduced iron (Fe-II) content, will be measured in the field *once each week* in the network of 7 monitoring points (MW02 and 6 new piezometers) in and near the pilot injection area. Groundwater samples will be collected *every two weeks* in the network of 7 monitoring points. At the end of the first month, groundwater samples will also be collected from existing monitoring points SB04, SB07R, SB08, and MW03. The samples will be analyzed for VOCs and the additional parameters identified in Section 4.2.3.1.

- *During the second and third months* after the injection, field parameters for groundwater will be determined in the field *every two weeks* in the network of 7 monitoring points (MW02 and the 6 new piezometers) in and near the pilot injection area. Groundwater samples will be collected *monthly* from the network of 7 monitoring points in and near the pilot injection area, as well as from existing monitoring points SB04, SB07R, SB08, and MW03. The samples will be analyzed for VOCs and the additional parameters identified in Section 4.2.3.1. The schedule for groundwater sampling in the network of 7 monitoring points in and near the pilot injection area might be adjusted if chemical conditions have changed significantly changed in the injection area, as suggested by field parameters.

- Groundwater sample collection and field parameter measurements in the full network of 11 monitoring points (6 new piezometers and 5 existing points) will be performed *once each month* during months 4-6 after the injection and quarterly thereafter until the end of the first year.

- At the end of the third month after injection and at the end of the first year, the CPT will be used to collect sediment core samples at 4-ft intervals through the vadose zone treatment interval (approximately 20-40 ft BGL) at the approximate location of previous Argonne boring SB12. The core samples will be analyzed for VOCs.

- Groundwater levels will be measured in the full network of monitoring points at the time of each sampling event noted above.

- Continued monitoring requirements after one year of the observation outlined above will be determined in consultation with the CCC/USDA and KDHE project managers.

4.2.4 Performance Evaluation of the ISCR Remedial Approach

The results of all sampling and monitoring activities performed under the monitoring program described in Section 4.2.3 will be compiled and presented to the CCC/USDA and the KDHE project managers for critical review following (1) the first 3 months (approximately 90 days) after injection of the EHC material and (2) at the end of 6 months after the EHC injection. If the CCC/USDA and the KDHE concur that the ISCR approach is effective in reducing the carbon tetrachloride concentrations in the targeted treatment area to acceptable levels, the CCC/USDA will request KDHE approval for implementation of this technology at the two remaining hot-spot areas targeted under this IM. If approval is received, the CCC/USDA and Argonne will submit a supplementary engineering design outlining the specifications to be used for the treatment and monitoring of the additional hot-spot areas.

4.3 Cost Estimate

The cost estimate will be included in the pilot study engineering design when the ISCR approach has been accepted. The cost estimate will include the following components:

- Adventus and installation contractor costs
- Argonne monitoring point placement costs
- Argonne professional management effort costs
- Laboratory analysis costs

4.4 Proposed Schedule

The proposed schedule for the pilot test will be included in the engineering design when the approach has been accepted.

Full implementation will follow upon evaluation by the CCC/USDA and KDHE project managers of the success of the pilot test.

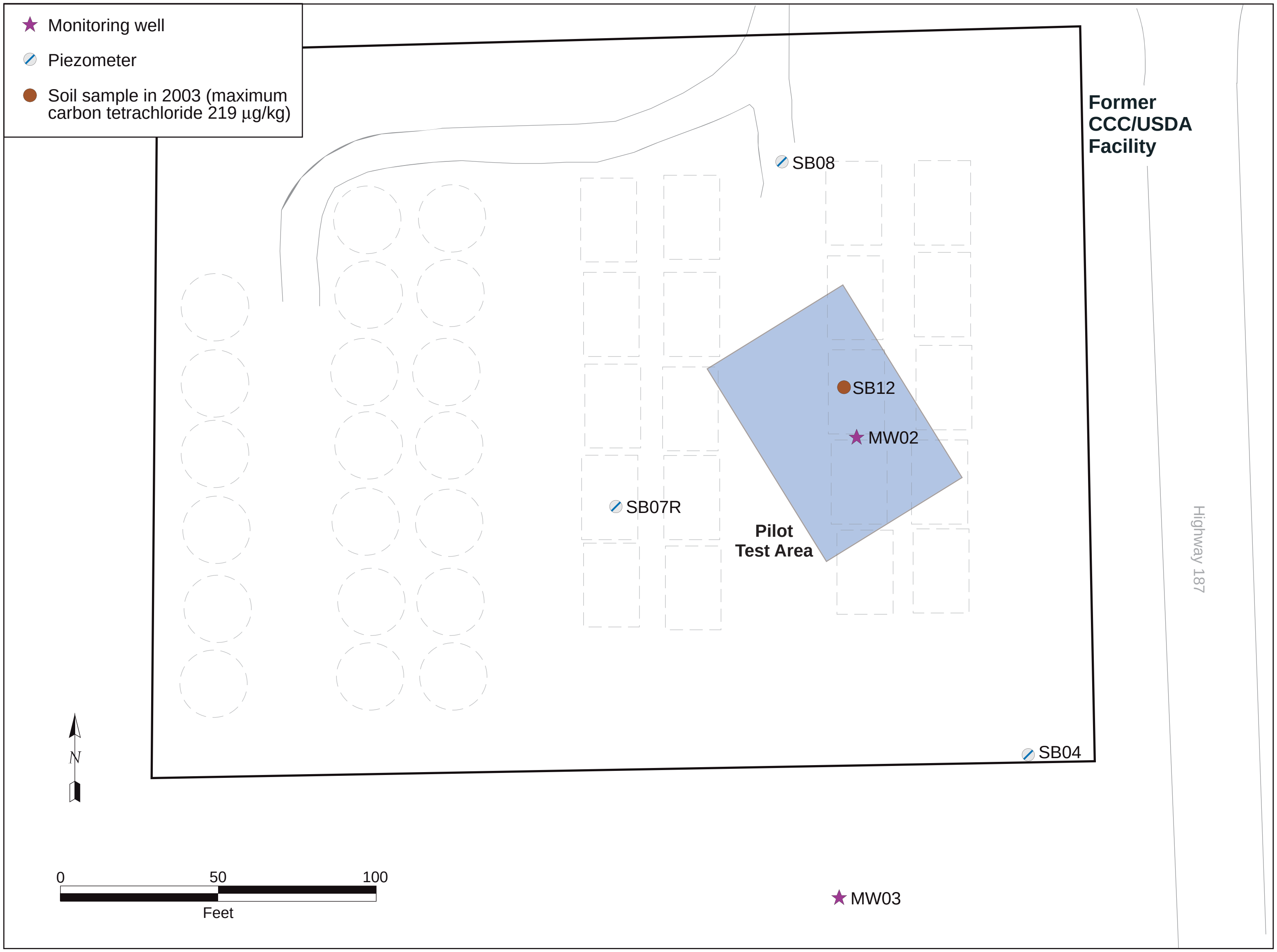

FIGURE 4.1 Proposed pilot test area at Centralia (45 ft x 75 ft), with locations of soil boring SB12 and MW02 (which define the hot-spot area to be treated in the pilot test) and nearby existing monitoring points.

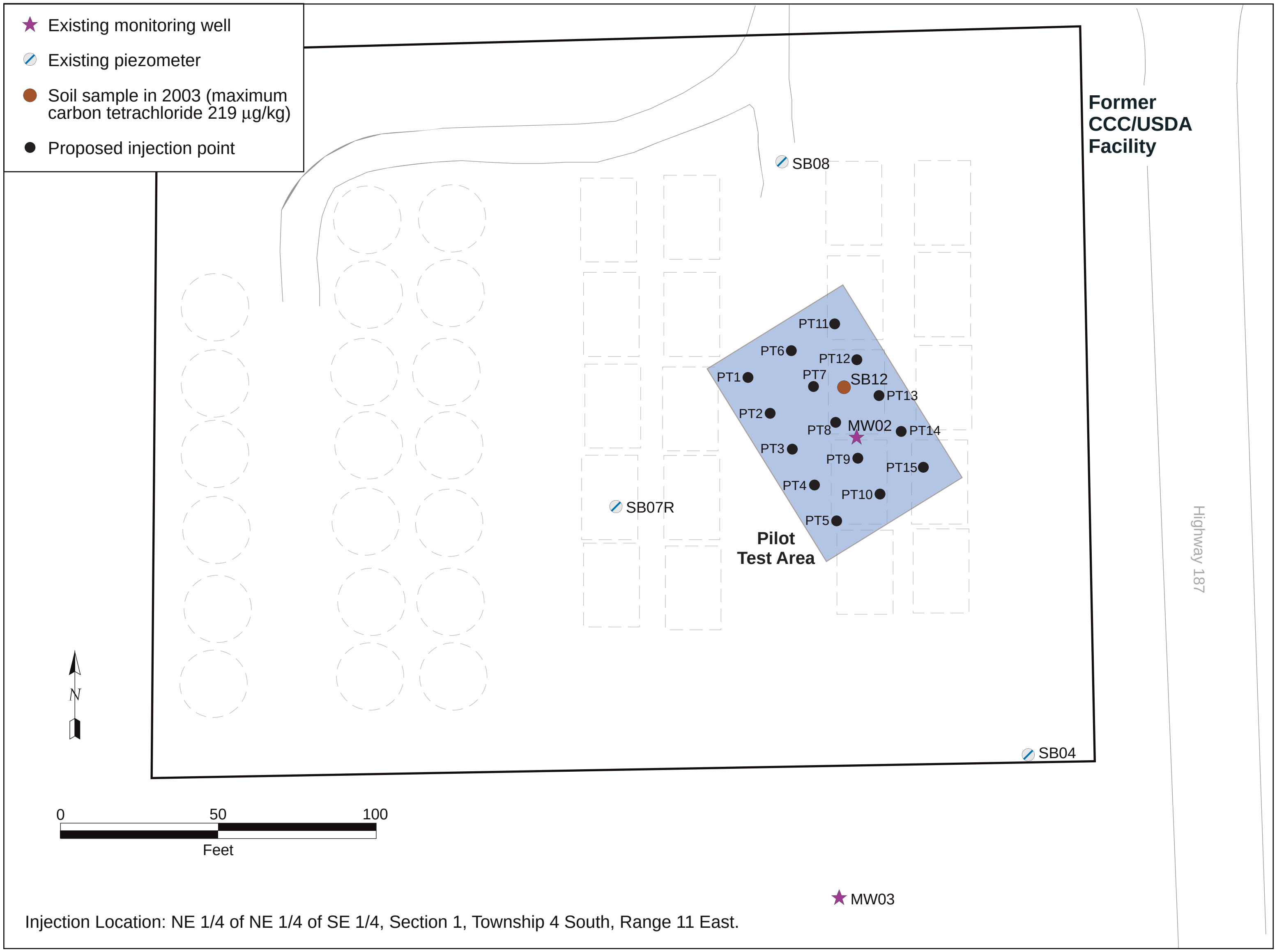

FIGURE 4.2 Proposed pilot test area at Centralia (45 ft x 75 ft), with locations of injection points (spaced on a 15-ft grid, with an anticipated radius of influence of 7.5 ft).

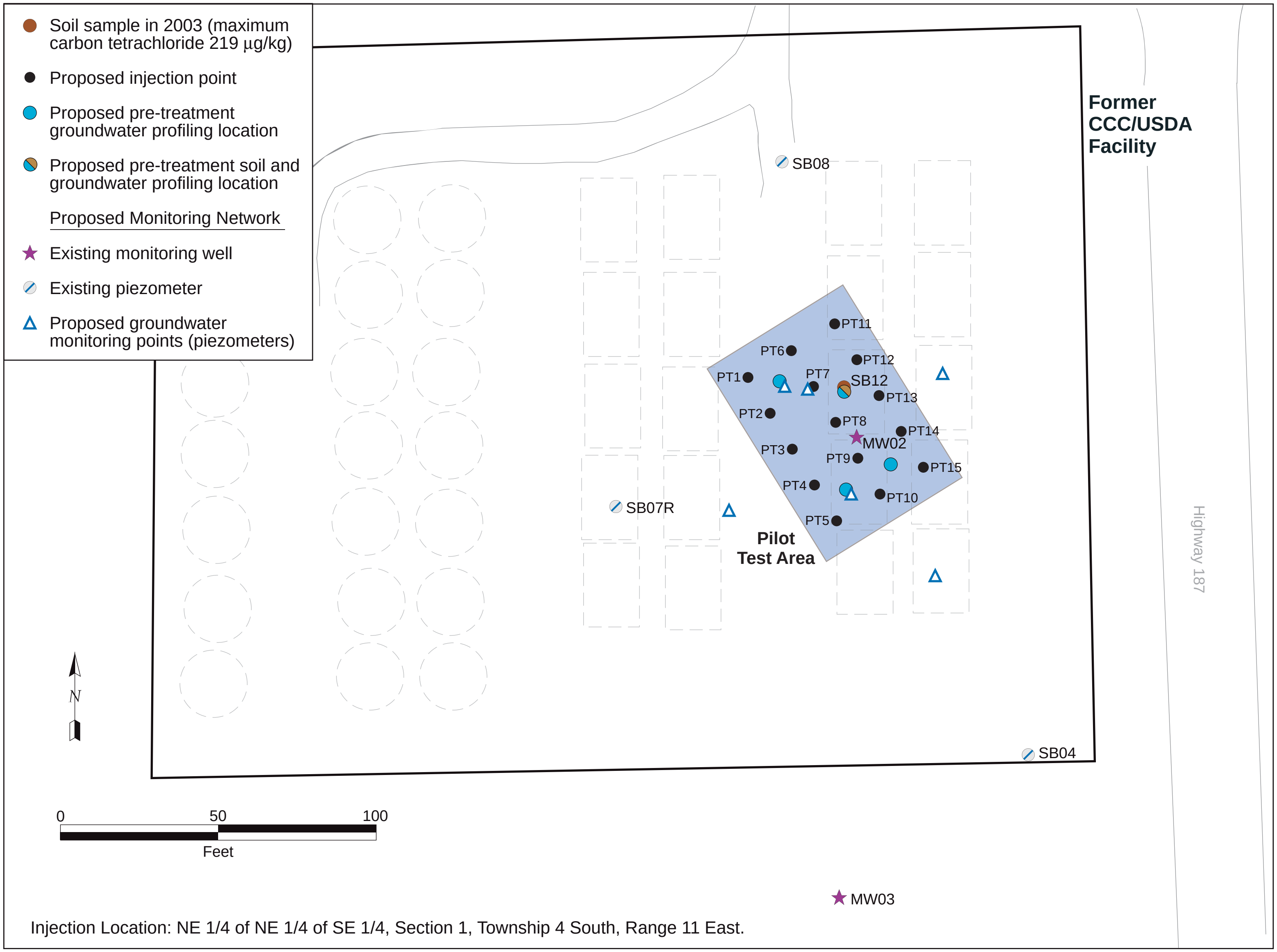

FIGURE 4.3 Proposed pilot test area at Centralia (45 ft x 75 ft), with locations of injection points (spaced on a 15-ft grid) and existing and new monitoring points.

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Appendix A:

Slug Testing of Monitoring Wells and Piezometers at Centralia (October 2006)

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Slug Testing of Monitoring Wells and Piezometers at Centralia (October 2006)

A.1 Background

Argonne's investigations at Centralia (Argonne 2003, 2004) demonstrated that the shallow aquifer affected by the carbon tetrachloride contamination is composed of glacial outwash sediments ranging from fine grained silts and clay to gravelly, medium to coarse sands. The areal and vertical distribution of these sediment types is heterogeneous; relatively thicker deposits of coarser grained sands and gravels have been identified in the eastern, northern, and western portions of the study area, while silts and clays are more prominently developed in the area near the southwestern corner of the former CCC/USDA facility (Figure 1.4). This distribution qualitatively mirrors persistent water level patterns observed at the site, which indicate that hydraulic gradients increase rapidly toward the southwestern corner of the former facility (Figure 1.7). Together, these data suggested that the observed variations in hydraulic gradients largely reflect spatial variations in the hydraulic conductivity of the aquifer sediments.

With the approval of the CCC/USDA, Argonne conducted single-well response ("slug") testing of selected monitoring wells and piezometers at Centralia to obtain quantitative information on the *in situ* hydraulic properties of the shallow aquifer. The results of these tests are summarized below.

A.2 Investigation Methods

Slug testing was performed at Centralia on October 23-25, 2006, at monitoring wells MW01, MW02, MW04, MW06, MW07, MW08, and MW10 and piezometers SB01, SB04, SB05, SB07R, and SB08. The locations are shown relative to the former CCC/USDA facility and the carbon tetrachloride plume in Figure 1.8. All of the locations tested have been purged repeatedly in conjunction with the extended monitoring program in progress at this site (Argonne 2005a); no additional efforts to develop each boring were therefore made prior to the hydraulic testing.

The tests at MW02, MW08, MW10, SB04, SB05, SB07R, and SB08 were performed by using pressurized air to depress and stabilize the water level in the well or piezometer casing. To initiate each test, the air pressure was released to create a condition equivalent to an instantaneous drop in head. The use of this pneumatic method proved logistically impractical for the tests at MW01, MW04, MW06, MW07, and SB01, because of the very long air pressure equilibration times required prior to the initiation of each test. This problem was a result of relatively low aquifer hydraulic conductivity; see Section A.3.

The slug tests at MW01, MW04, MW06, MW07, and SB01 were conducted by quickly lowering or withdrawing a physical slug into the casing to perturb the static water column. For this purpose, the following physical slugs were used: a 4-ft-long, 0.5-in.-diameter solid steel rod at SB01; a 4-ft-long, 1.5-in.-diameter sealed, sand-filled PVC [polyvinyl chloride] pipe at MW01, MW04, and MW06; and a 3-ft-long, 1.25-in.-diameter sealed, sand-filled PVC pipe at MW07.

The water level responses for all of the tests performed by using the air pressurization method, as well as for the physical slug test performed at MW01, were recorded by using a downhole pressure transducer connected to an automatic data logger (Hermit™ 1000C). Water level responses for the remaining tests were recorded by using self-contained, downhole pressure-sensing and data-logging units (MiniTroll™ Pro Model). Both sensing and recording systems permitted data acquisition at high rates.

The slug test procedure was performed three times at MW02, MW08, MW10, SB04, SB05, and SB08. Because of prolonged response times, the procedure was performed only twice at MW04, MW06, MW07, SB01, and SB07R and once at MW01.

A.3 Results and Discussion

The overall results of the slug tests are summarized in Figure A.1. Representative interpretations for the individual tests are in Figures A.2-A.13. The figures are grouped after the text of Appendix A.

The hydraulic conductivity estimates resulting from the slug tests are summarized in Table A.1. Complete data (time versus residual drawdown) for the slug tests and the well (or piezometer) construction parameters required for data analysis are in Tables A.12-A.13. The data tables are grouped at the end of Appendix A, after the figures.

To generate estimates of hydraulic conductivity, the water level response data generated by the slug tests at Centralia were interpreted by using the analysis methods of Bouwer and Rice (Bouwer and Rice 1976; Bouwer 1989) and Hvorslev (1951), as implemented in the commercial well test software analysis package AqteSolv for Windows. Numerous alternative slug test analysis methods have been developed, each with advantages and disadvantages. The methods used for this study were selected in light of their relatively wide applicability, their level of documentation and general acceptance by the scientific community, and their ease of implementation to achieve the objective of estimating hydraulic parameters for the aquifer materials.

Representative (manual) curve fits for the test data are in Figures A.2-A.13. The hydraulic conductivity values calculated for each location by using either analysis method are dependent, in part, on the assumed thickness of the aquifer that responds to the water level offset produced during a test. Unambiguous identification of the effective aquifer interval affected by slug testing is difficult at numerous locations at Centralia because of the silty to clayey character of the sediments generally present. In light of this observation and the relatively small volume of water displaced during each slug test, hydraulic conductivities were estimated under the assumption that a thickness of sediments equal to the associated screen length contributed to the water level response at each tested location. The resulting hydraulic conductivity estimates are summarized in Table A.1. For each data set (Tables A.2-A.13), the estimated hydraulic conductivity values calculated with the Bouwer and Rice method were of the same magnitude as, but roughly 25% lower than, values for the same data set calculated with the Hvorslev method.

The estimated hydraulic conductivity values for the shallow aquifer sediments at Centralia ranged over four orders of magnitude, from approximately 0.001 ft/day at SB01 to approximately 22 ft/day at SB08. The values calculated by using the Hvorslev method are in Figure A.1. The areal distribution of hydraulic conductivities estimated by using *either* analysis method support the interpretation of water level and lithologic data outlined above.

The results indicate a significant reduction in the permeability of the aquifer materials associated with the increased hydraulic gradients near the southwest corner of the former CCC/USDA facility (roughly parallel to its southern boundary). The estimated hydraulic conductivities associated with the coarser grained deposits identified at MW02, SB04, SB05, and SB08 range from roughly 2 ft/day to approximately 22 ft/day. In contrast, those near the southern margin of the former facility are consistently less than approximately 0.2 ft/day.

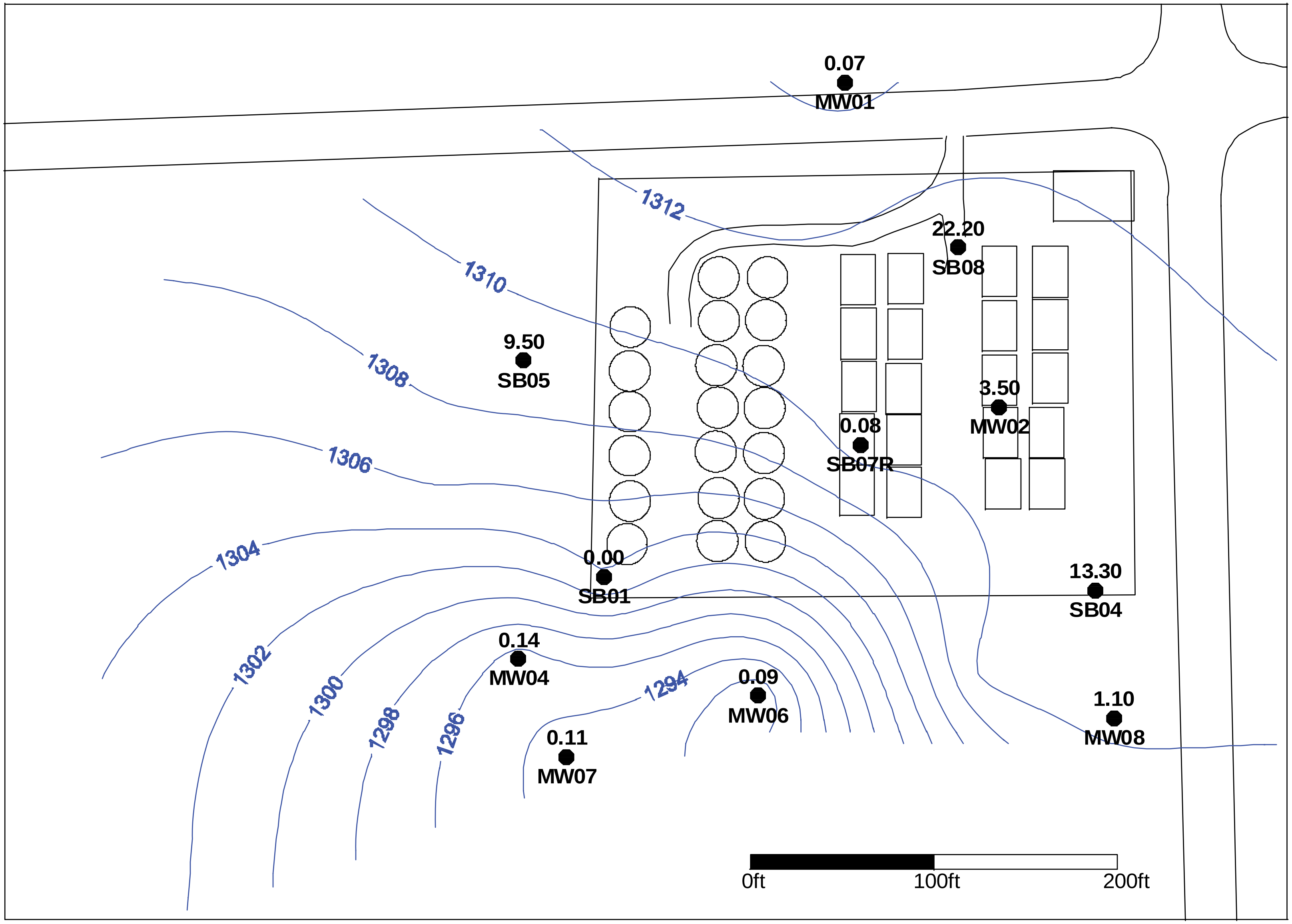
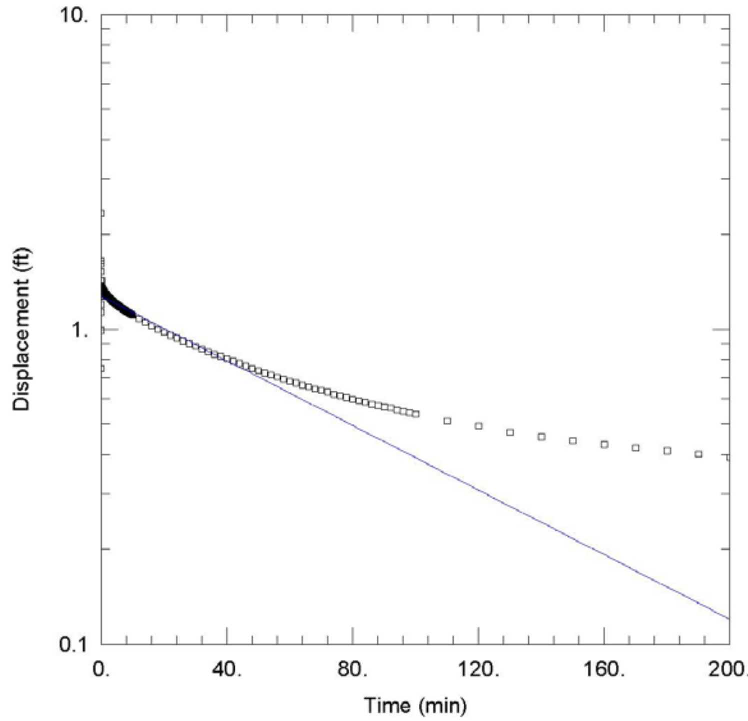
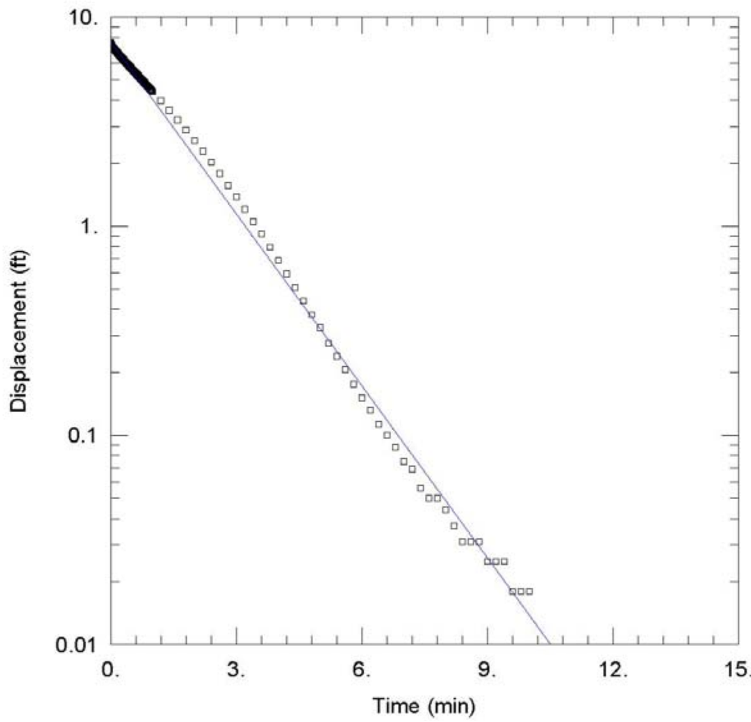


FIGURE A.1 Potentiometric surface at Centralia, based on water levels measured manually on June 16, 2006, and estimates of hydraulic conductivity (calculated by using the Hvorslev method) from slug tests performed on October 23-25, 2006.

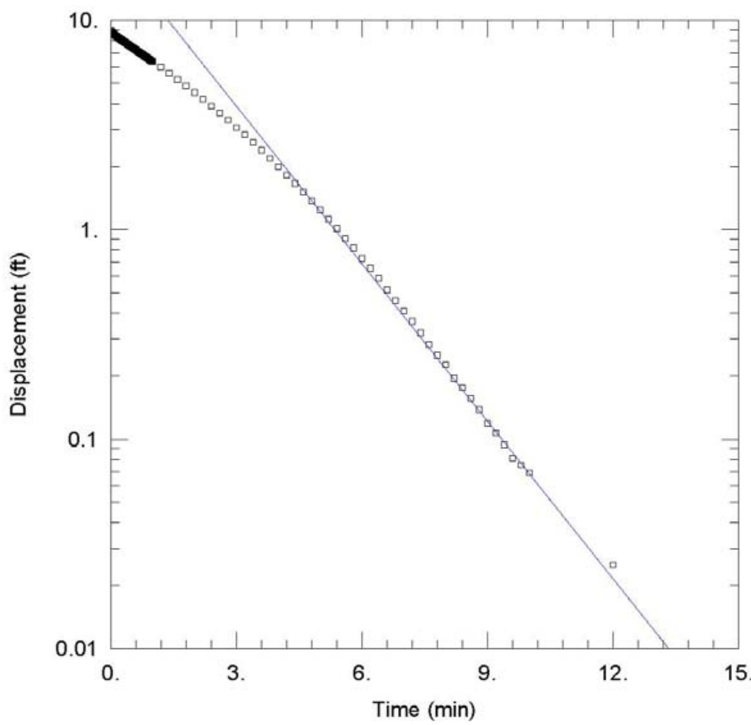


Observed slug test water level response and interpretive straight-line fit to the measured data for MW01, Slug In.

FIGURE A.2 Observed slug test water level response and interpretive fit for the data for MW01 shown in Table A.2.

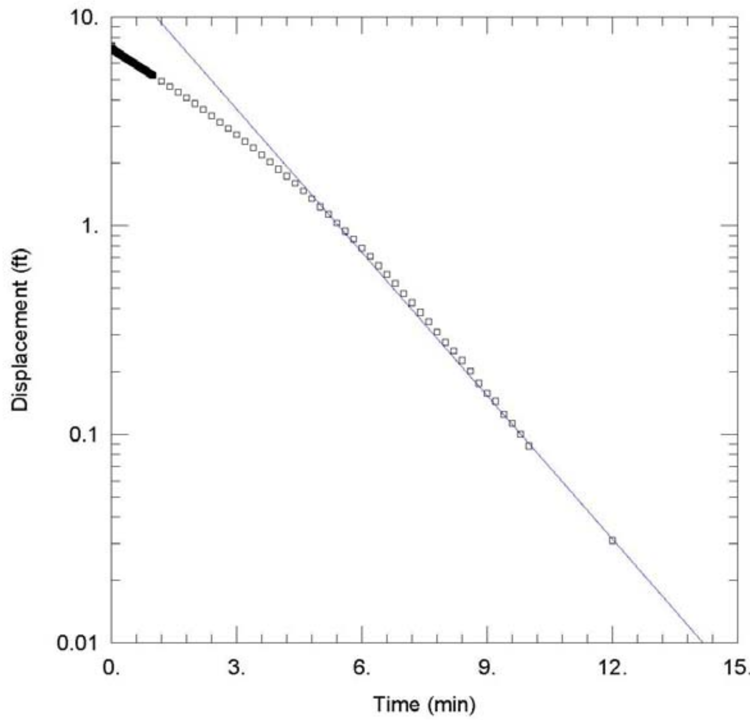


Observed slug test water level response and interpretive straight-line fit to the measured data for MW02 Test 2, Step 0.



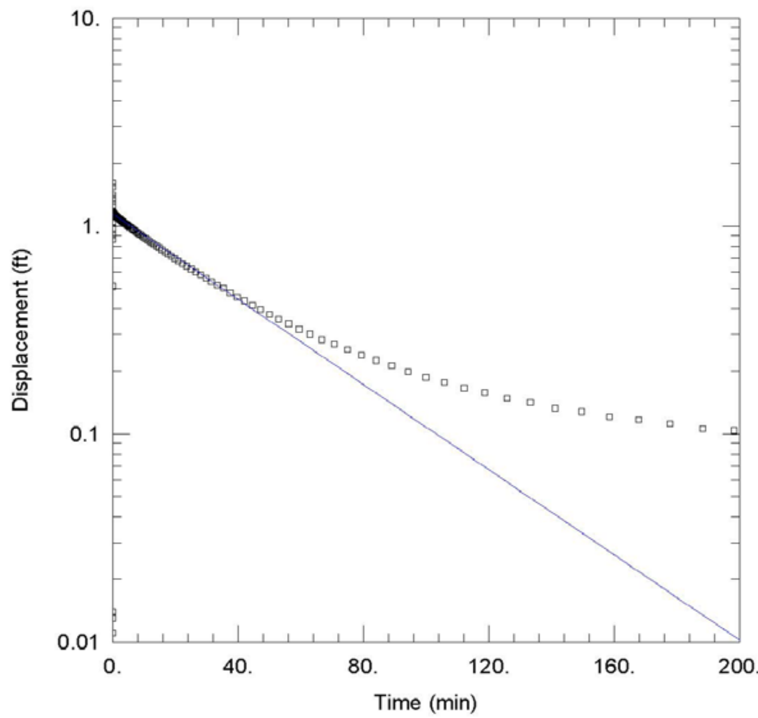
Observed slug test water level response and interpretive straight-line fit to the measured data for MW02 Test 2, Step 1.

FIGURE A.3 Observed slug test water level response and interpretive fit for the data for MW02 shown in Table A.3.

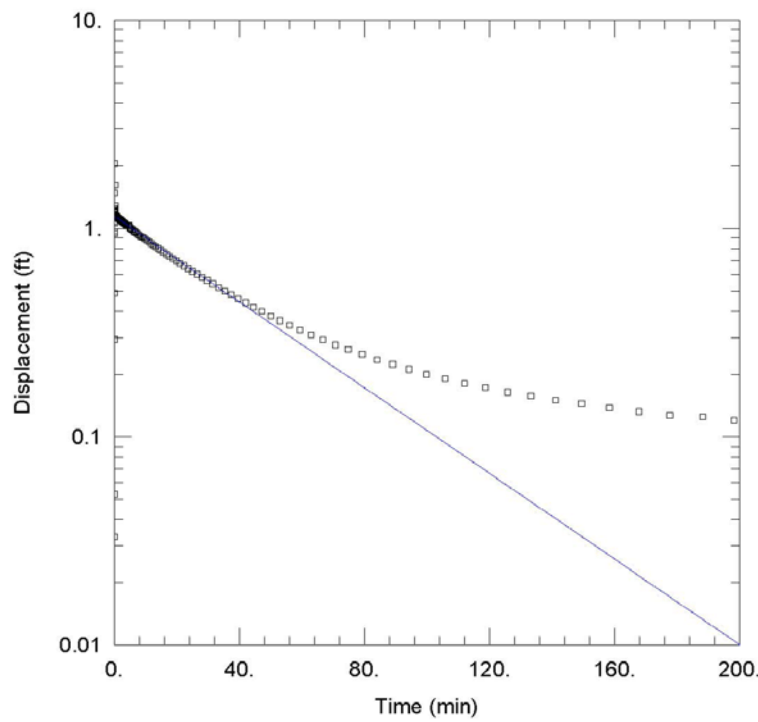


Observed slug test water level response and interpretive straight-line fit to the measured data for MW02 Test 2, Step 2.

FIGURE A.3 (Cont.)

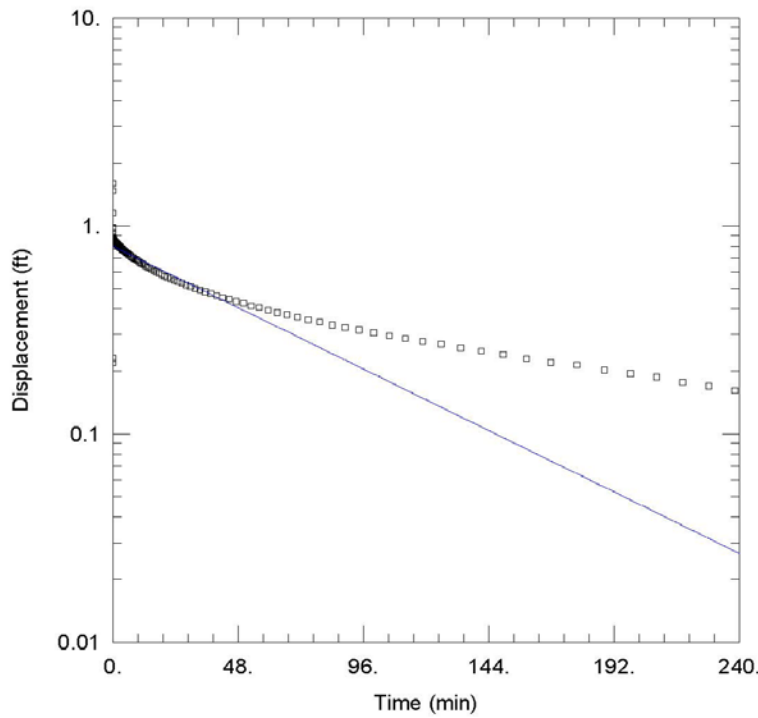


Observed slug test water level response and interpretive straight-line fit to the measured data for MW04 Slug In.

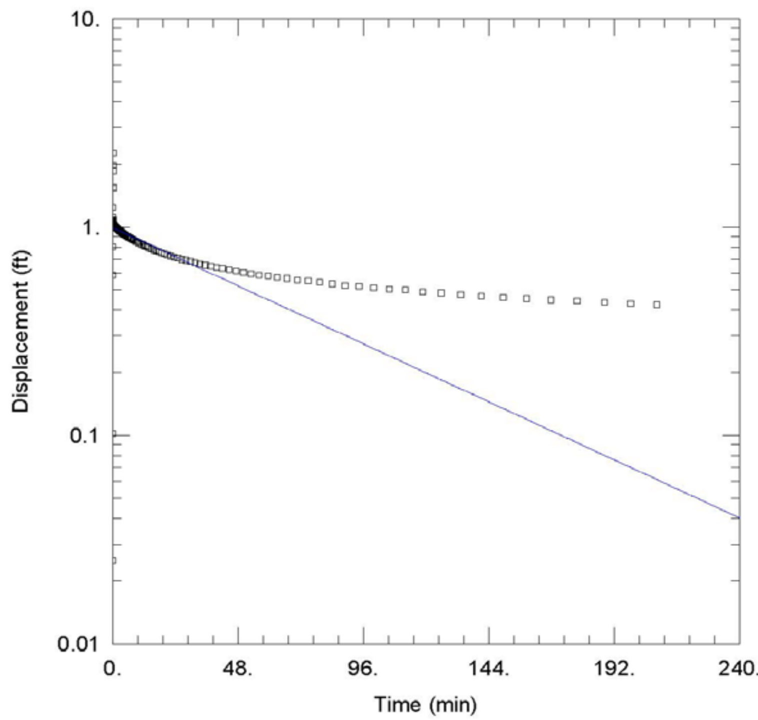


Observed slug test water level response and interpretive straight-line fit to the measured data for MW04 Slug Out.

FIGURE A.4 Observed slug test water level response and interpretive fit for the data for MW04 shown in Table A.4.

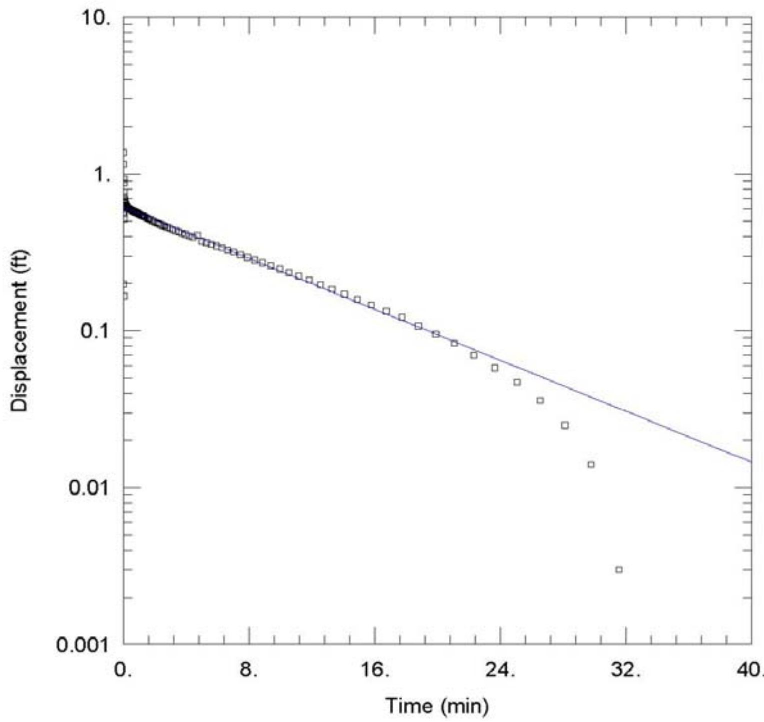


Observed slug test water level response and interpretive straight-line fit to the measured data for MW06 Slug In.

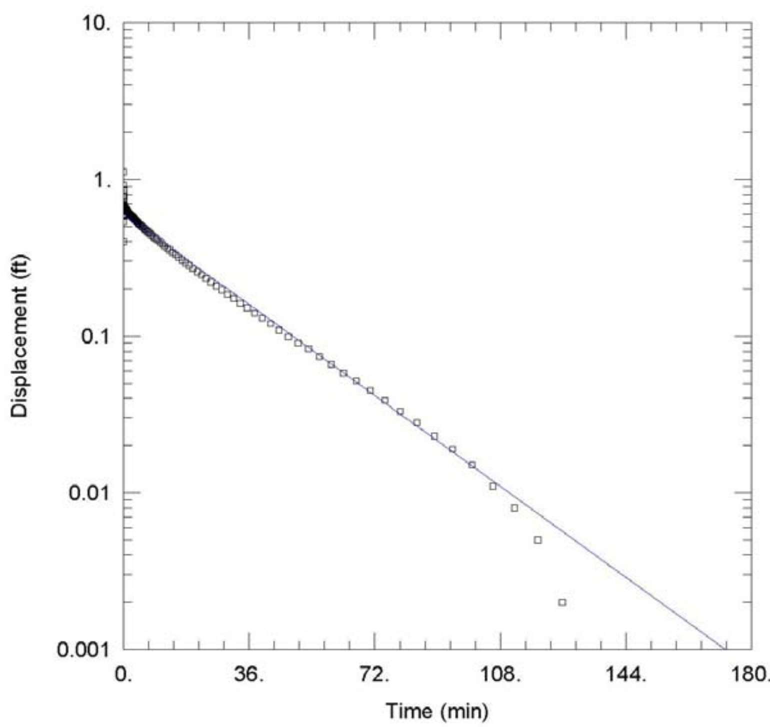


Observed slug test water level response and interpretive straight-line fit to the measured data for MW06 Slug Out.

FIGURE A.5 Observed slug test water level response and interpretive fit for the data for MW06 shown in Table A.5.

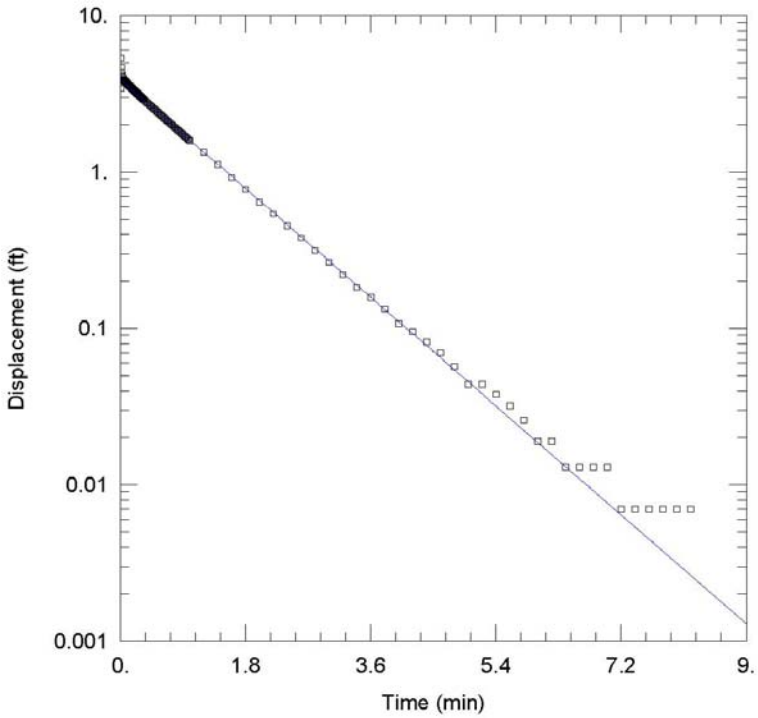


Observed slug test water level response and interpretive straight-line fit to the measured data for MW07 Slug In.

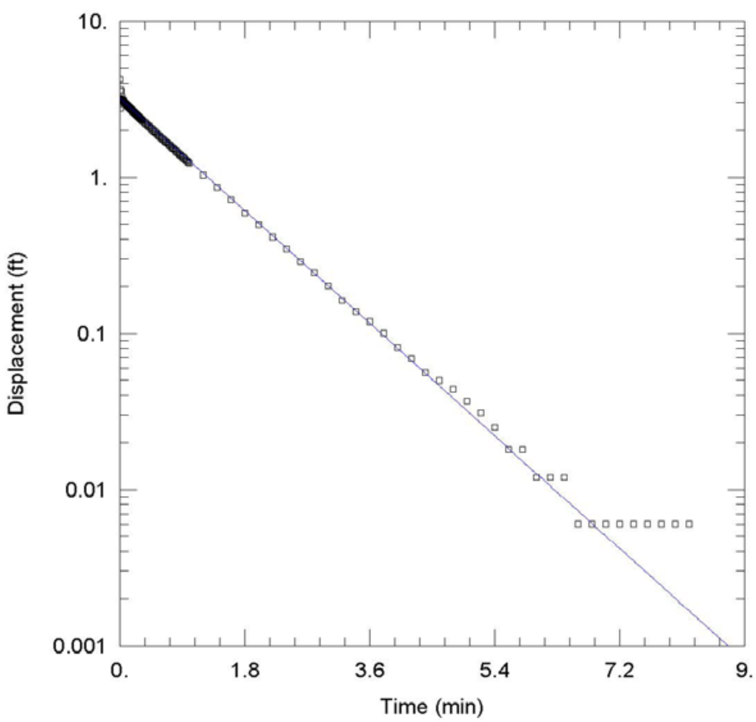


Observed slug test water level response and interpretive straight-line fit to the measured data for MW07 Slug Out.

FIGURE A.6 Observed slug test water level response and interpretive fit for the data for MW07 shown in Table A.6.

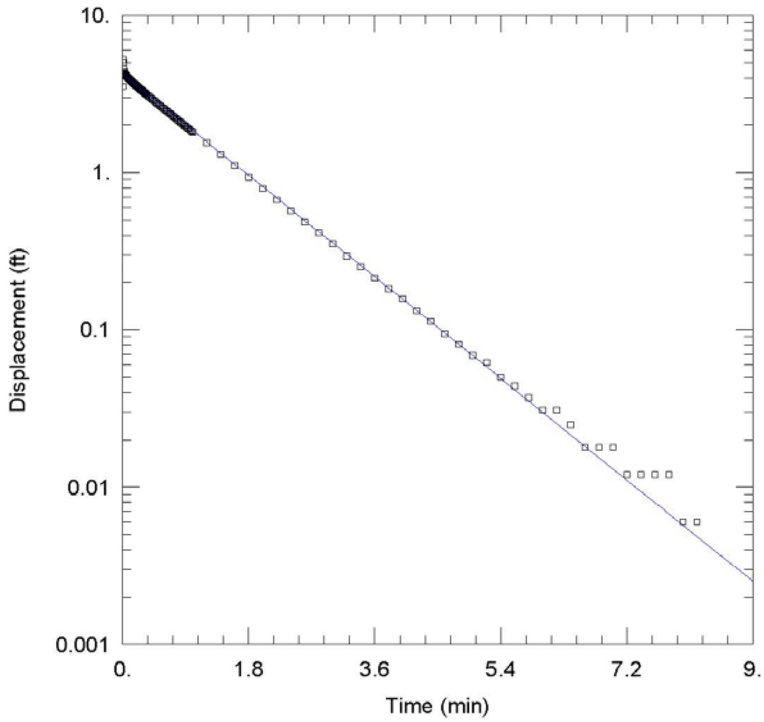


Observed slug test water level response and interpretive straight-line fit to the measured data for MW08 Test 6, Step 0.



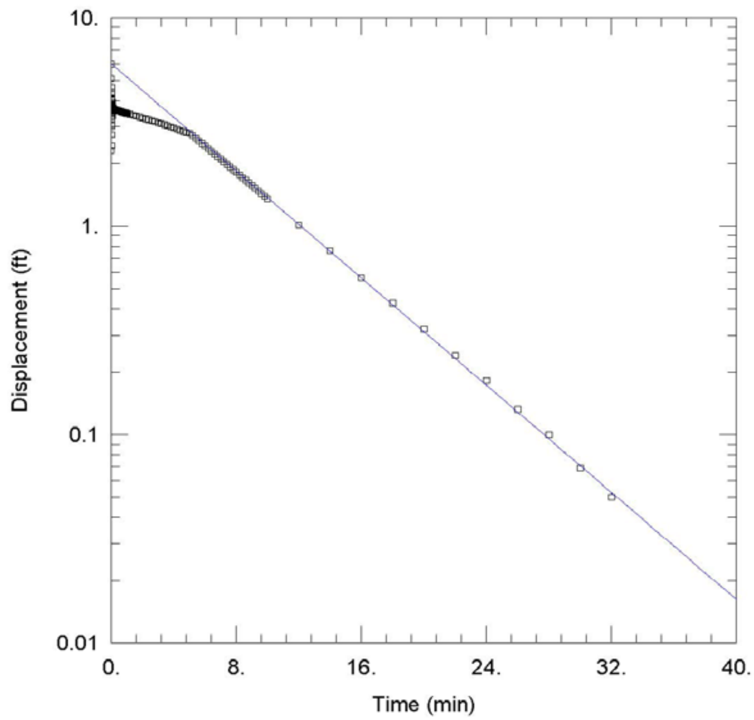
Observed slug test water level response and interpretive straight-line fit to the measured data for MW08 Test 7, Step 0.

FIGURE A.7 Observed slug test water level response and interpretive fit for the data for MW08 shown in Table A.7.

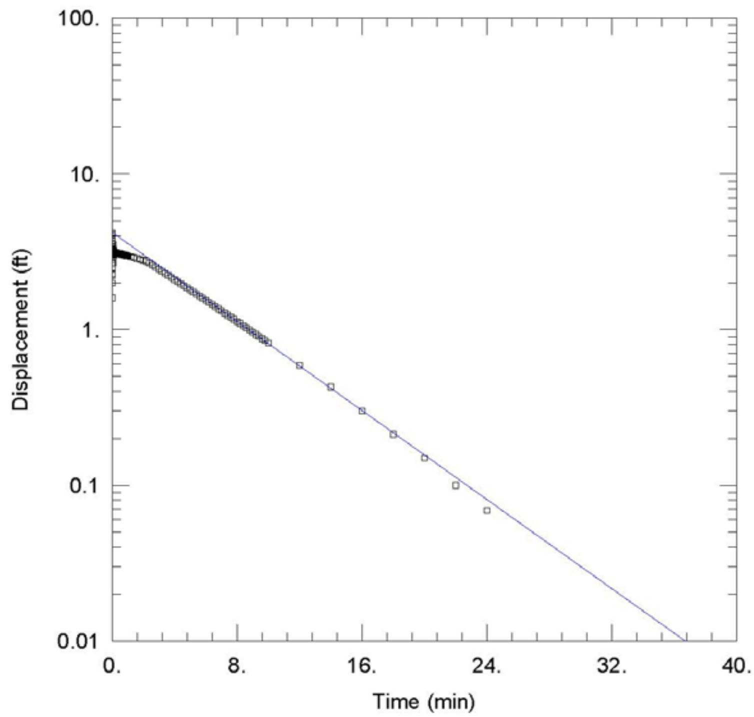


Observed slug test water level response and interpretive straight-line fit to the measured data for MW08 Test 7, Step 1.

FIGURE A.7 (Cont.)

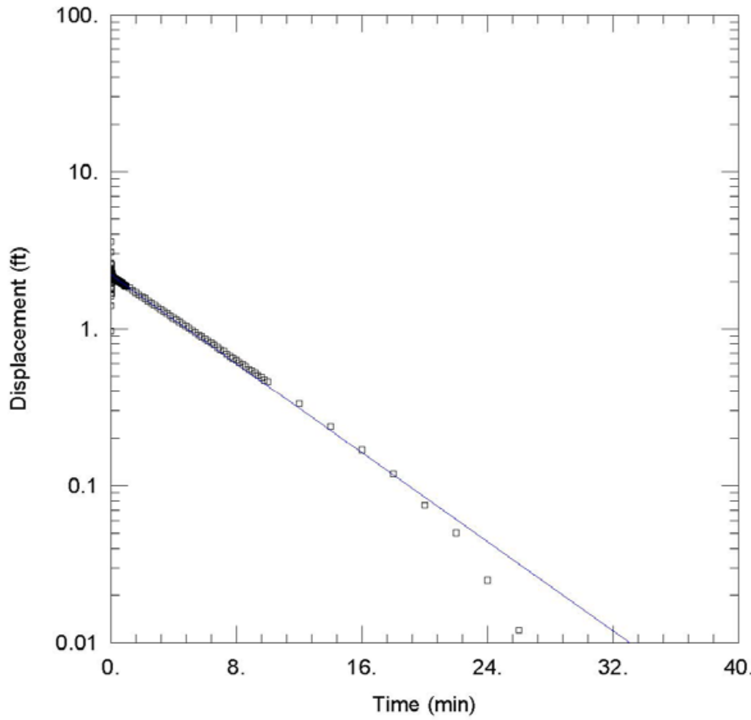


Observed slug test water level response and interpretive straight-line fit to the measured data for MW10 Test 0, Step 0.



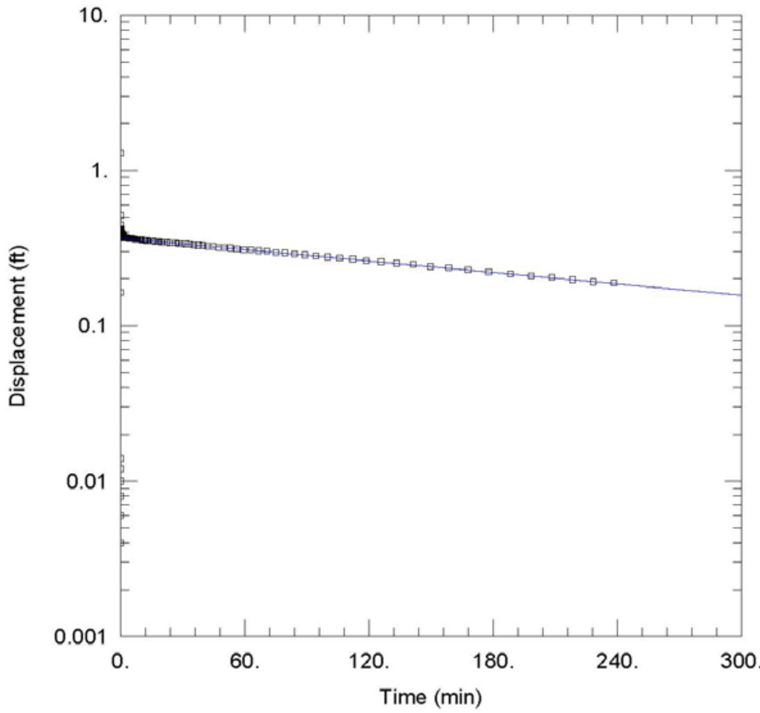
Observed slug test water level response and interpretive straight-line fit to the measured data for MW10 Test 0, Step 1.

FIGURE A.8 Observed slug test water level response and interpretive fit for the data for MW10 shown in Table A.8.

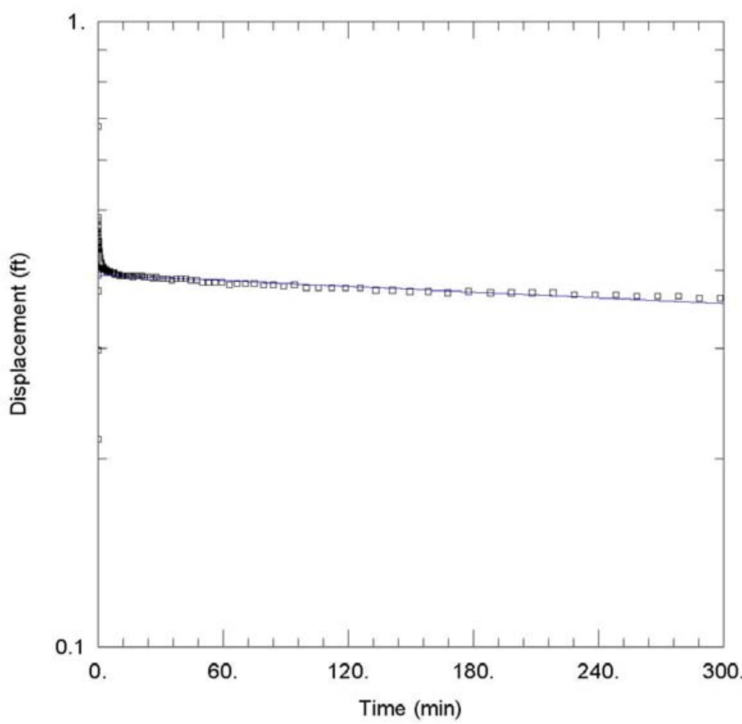


Observed slug test water level response and interpretive straight-line fit to the measured data for MW10 Test 0, Step 2.

FIGURE A.8 (Cont.)

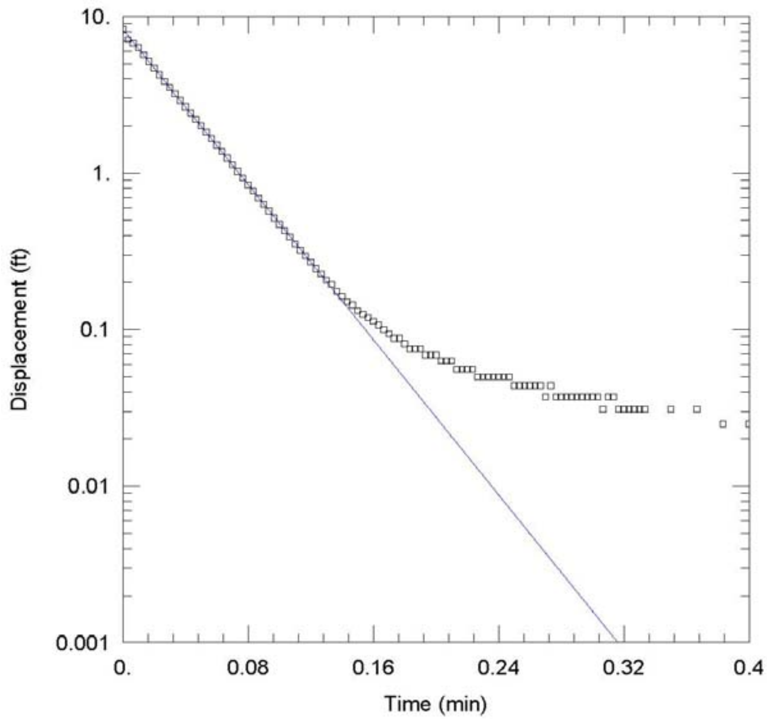


Observed slug test water level response and interpretive straight-line fit to the measured data for SB01 Slug In.

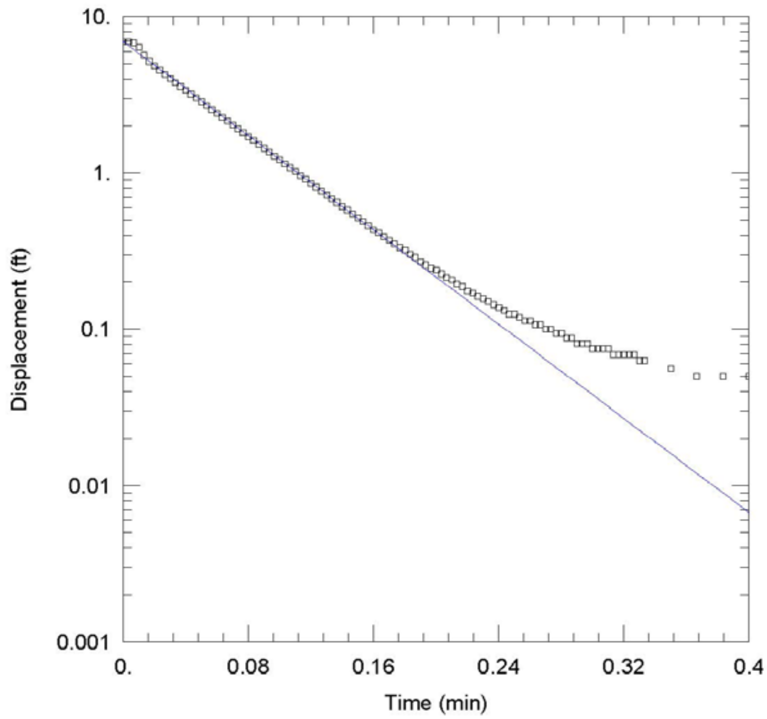


Observed slug test water level response and interpretive straight-line fit to the measured data for SB01 Slug Out.

FIGURE A.9 Observed slug test water level response and interpretive fit for the data for SB01 shown in Table A.9.

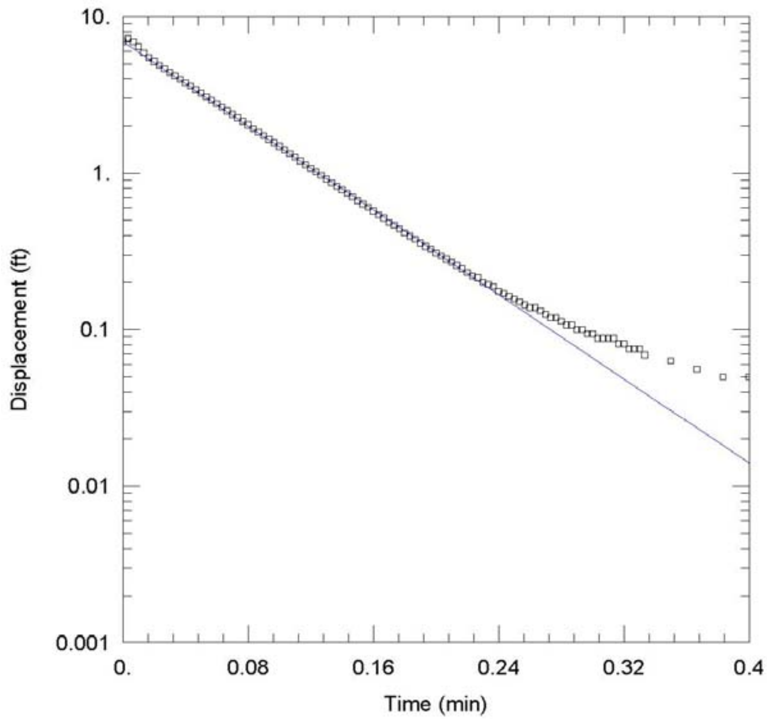


Observed slug test water level response and interpretive straight-line fit to the measured data for SB04 Test 1, Step 0.



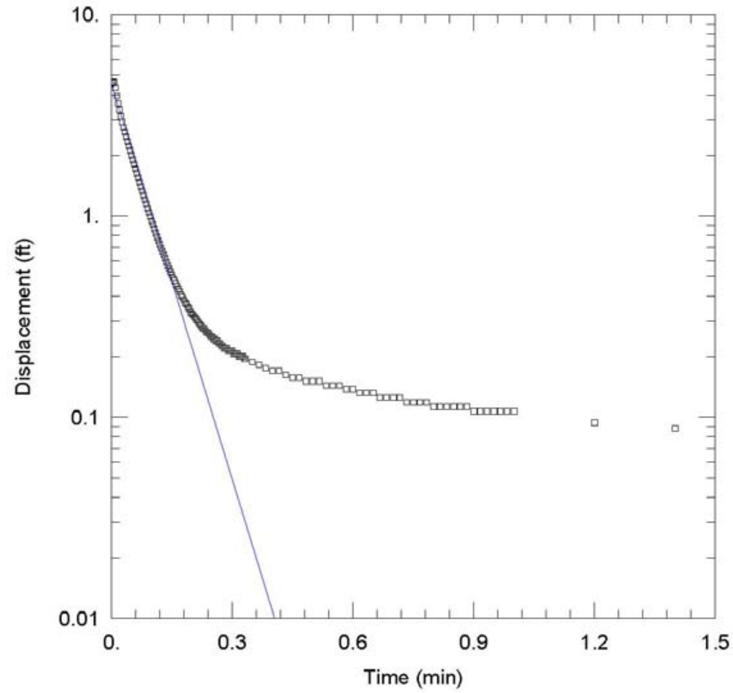
Observed slug test water level response and interpretive straight-line fit to the measured data for SB04 Test 1, Step 1.

FIGURE A.10 Observed slug test water level response and interpretive fit for the data for SB04 shown in Table A.10.

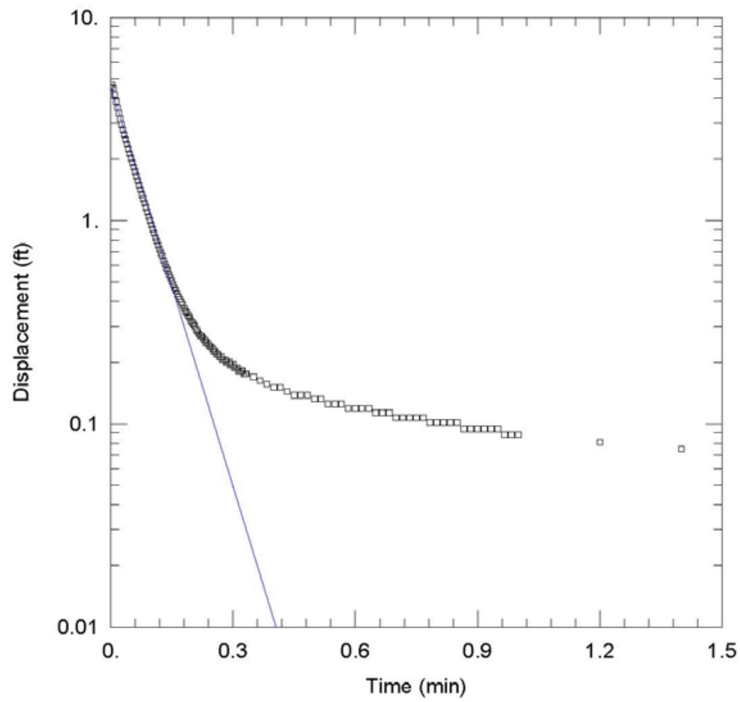


Observed slug test water level response and interpretive straight-line fit to the measured data for SB04 Test 1, Step 2.

FIGURE A.10 (Cont.)

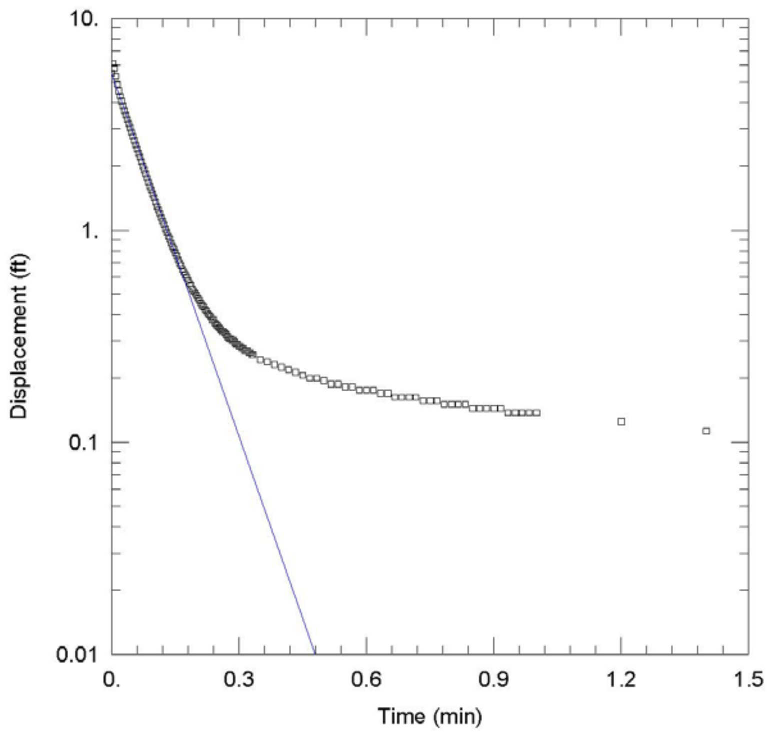


Observed slug test water level response and interpretive straight-line fit to the measured data for SB05 Test 5, Step 0.



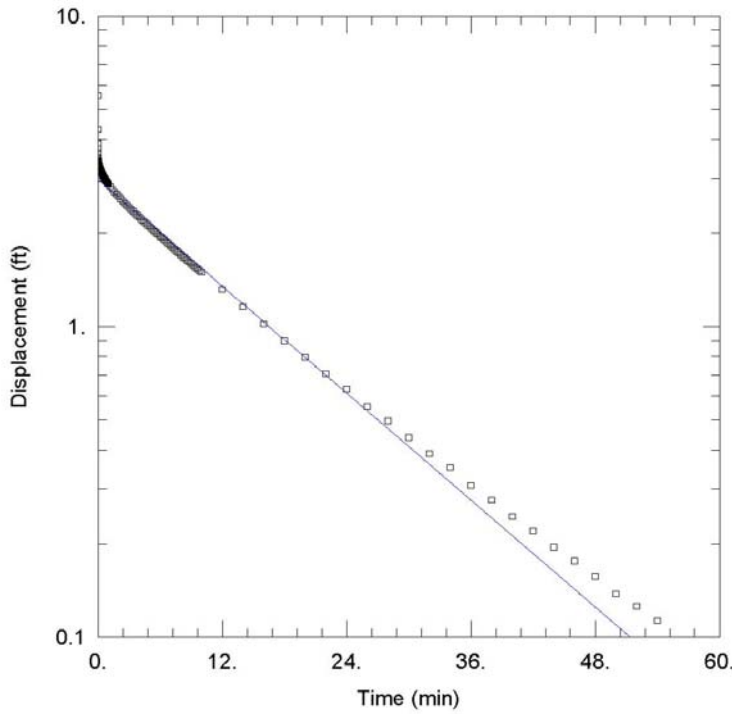
Observed slug test water level response and interpretive straight-line fit to the measured data for SB05 Test 5, Step 1.

FIGURE A.11 Observed slug test water level response and interpretive fit for the data for SB05 shown in Table A.11.

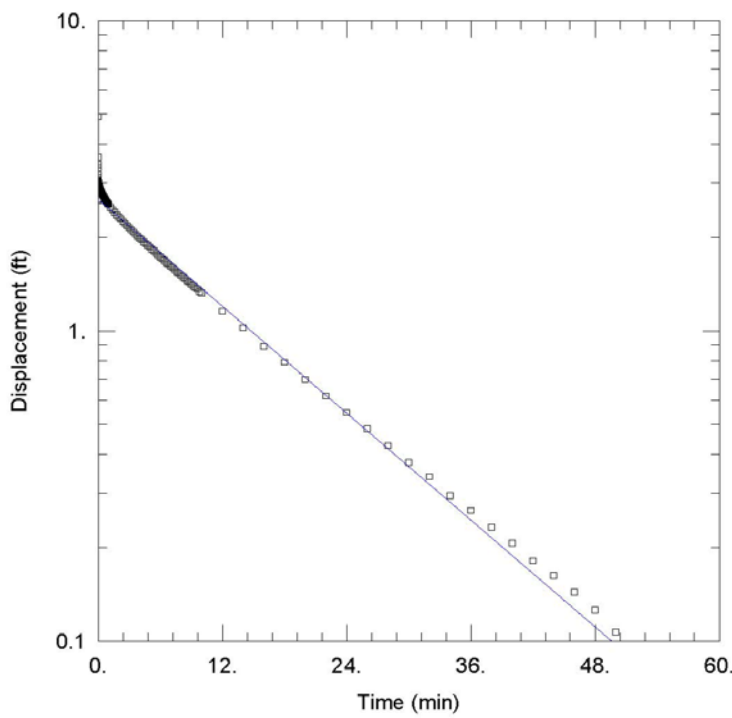


Observed slug test water level response and interpretive straight-line fit to the measured data for SB05 Test 5, Step 2.

FIGURE A.11 (Cont.)

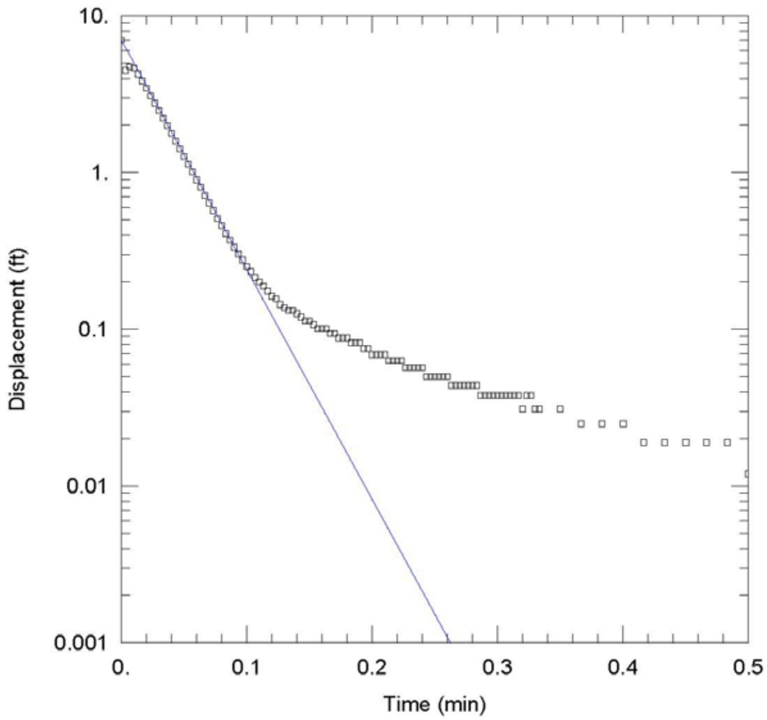


Observed slug test water level response and interpretive straight-line fit to the measured data for SB07R Test 4, Step 0.

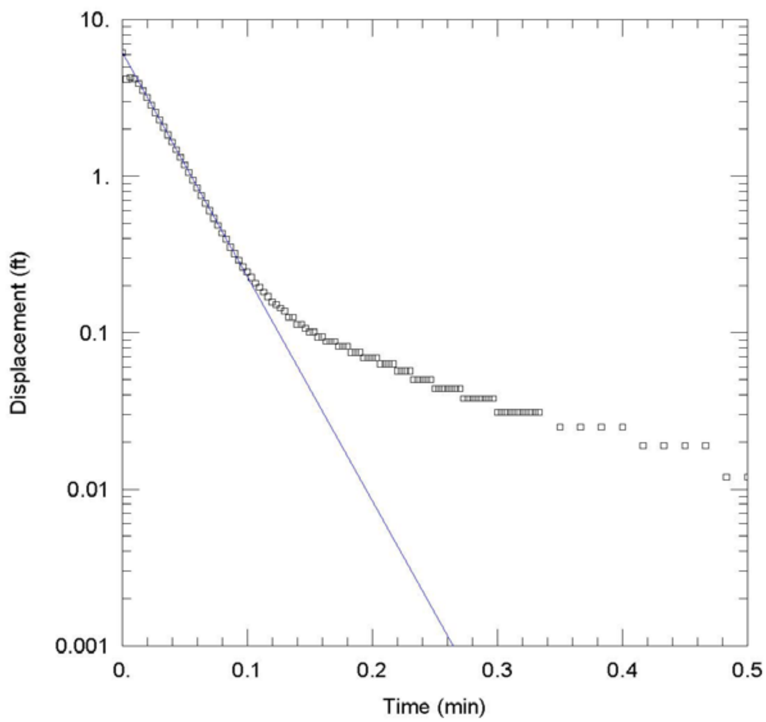


Observed slug test water level response and interpretive straight-line fit to the measured data for SB07R Test 4, Step 1.

FIGURE A.12 Observed slug test water level response and interpretive fit for the data for SB07R shown in Table A.12.

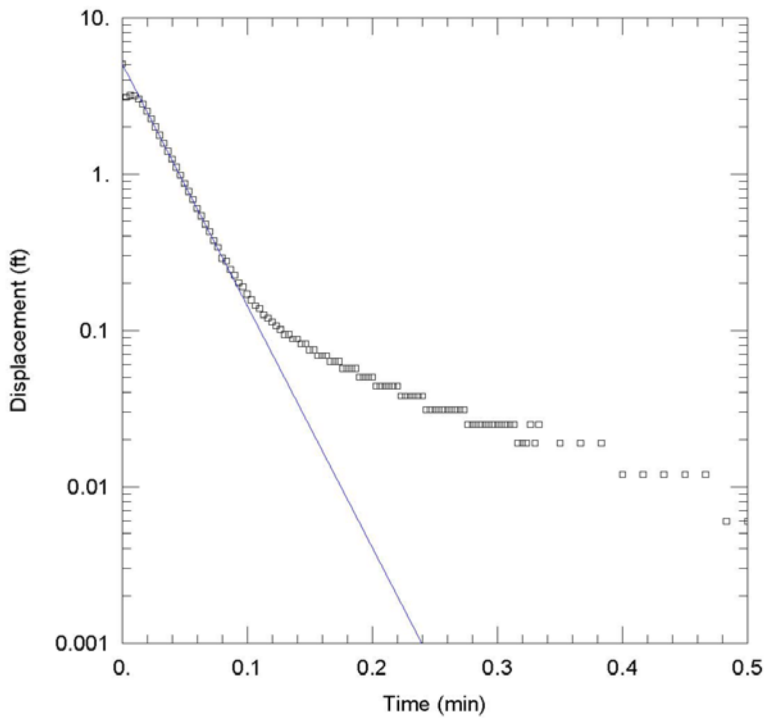


Observed slug test water level response and interpretive straight-line fit to the measured data for SB08 Test 3, Step 0.



Observed slug test water level response and interpretive straight-line fit to the measured data for SB08 Test 3, Step 1.

FIGURE A.13 Observed slug test water level response and interpretive fit for the data for SB08 shown in Table A.13.



Observed slug test water level response and interpretive straight-line fit to the measured data for SB08 Test 3, Step 2.

FIGURE A.13 (Cont.)

TABLE A.1 Summary of interpreted results for slug tests at Centralia, Kansas

Location	Diameter (in.)		Reported Well Depth[a] (ft BGL)	Measured Well Depth[b] (ft TOC)	Screen Interval[a] (ft BGL)	Calculated Hydraulic Conductivity[c] (ft/day)						Estimated Permeability[d] (darcy)
	Casing	Hole				Bouwer and Rice Method			Hvorslev Method			
MW01[e]	4	11.5	67	69.55	54.5-64.5	0.05			0.07			0.02-0.03
MW02	4	11.5	62	61.32	49.5-59.5	2.85	2.61	2.38	3.84	3.51	3.21	0.98-1.57
MW04[e]	4	11.5	50	49.25	37.5-47.5	0.11	0.11		0.14	0.14		0.05-0.06
MW06[e]	4	11.5	65	60.03	46.5-56.5	0.06	0.06		0.09	0.08		0.02-0.04
MW07[e]	2	8.25	60	58.47	45-55	0.12	0.05		0.16	0.06		0.02-0.07
MW08	2	8.25	58	57.41	38-53	0.85	0.89	0.79	1.13	1.17	1.05	0.32-0.48
MW10	2	8.25	50	47.73	30-45	0.14	0.16	0.16	0.19	0.21	0.21	0.06-0.09
SB01[e]	1	1.3	50	48.96	40-50	0.001	<0.001		0.002	<0.001		<0.001
SB04	1	1.3	61	59.16	51-61	14.5	8.79	7.85	18.6	11.3	10.1	3.22-7.62
SB05	1	1.3	42	40.82	32-42	7.64	7.64	6.68	9.94	9.82	8.58	2.74-4.07
SB07R	2	8.25	60	58.54	45-60	0.06	0.06		0.08	0.08		0.02-0.03
SB08	1	1.3	62	59.80	52-62	17.1	16.7	18.1	22.0	21.5	23.0	6.84-9.43

[a] Well parameters reported in construction logs and registrations.

[b] Well depth from top of casing, measured in September 2006.

[c] Caculated with the assumption that the effect of the slug test was dissipated over an aquifer thickness equal to the screen length.

[d] Intrinsic permeability estimated under the assumption of "pure" groundwater at the laboratory standard of 15.6°C.

[e] Tests performed with a solid slug because of the long response time; all others were performed with the air pressurization method.

TABLE A.2 Slug test data for boring MW01 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.1667 ft; borehole radius = 0.4792 ft; Kz/Kr = 1).

Elapsed Time (min)	Residual Drawdown (ft)	Elapsed Time (min)	Residual Drawdown (ft)	Elapsed Time (min)	Residual Drawdown (ft)	Elapsed Time (min)	Residual Drawdown (ft)
0	1.869	0.1366	1.354	0.2733	1.344	0.7166	1.322
0.0033	1.197	0.14	1.354	0.2766	1.344	0.7333	1.319
0.0066	2.332	0.1433	1.357	0.28	1.348	0.75	1.319
0.01	1.313	0.1466	1.354	0.2833	1.344	0.7666	1.319
0.0133	0.75	0.15	1.354	0.2866	1.344	0.7833	1.319
0.0166	1.278	0.1533	1.354	0.29	1.344	0.8	1.319
0.02	1.612	0.1566	1.354	0.2933	1.348	0.8166	1.316
0.0233	1.646	0.16	1.354	0.2966	1.344	0.8333	1.316
0.0266	1.131	0.1633	1.354	0.3	1.344	0.85	1.316
0.03	0.989	0.1666	1.354	0.3033	1.344	0.8666	1.313
0.0333	1.423	0.17	1.357	0.3066	1.344	0.8833	1.313
0.0366	1.527	0.1733	1.357	0.31	1.344	0.9	1.313
0.04	1.37	0.1766	1.351	0.3133	1.344	0.9166	1.313
0.0433	1.291	0.18	1.354	0.3166	1.344	0.9333	1.313
0.0466	1.332	0.1833	1.354	0.32	1.341	0.95	1.31
0.05	1.423	0.1866	1.354	0.3233	1.344	0.9666	1.31
0.0533	1.379	0.19	1.351	0.3266	1.344	0.9833	1.31
0.0566	1.332	0.1933	1.354	0.33	1.341	1	1.31
0.06	1.357	0.1966	1.354	0.3333	1.344	1.2	1.297
0.0633	1.379	0.2	1.351	0.35	1.341	1.4	1.291
0.0666	1.373	0.2033	1.351	0.3666	1.341	1.6	1.285
0.07	1.354	0.2066	1.354	0.3833	1.338	1.8	1.278
0.0733	1.357	0.21	1.348	0.4	1.338	2	1.272
0.0766	1.366	0.2133	1.354	0.4166	1.338	2.2	1.263
0.08	1.363	0.2166	1.348	0.4333	1.338	2.4	1.26
0.0833	1.357	0.22	1.351	0.45	1.335	2.6	1.253
0.0866	1.357	0.2233	1.351	0.4666	1.335	2.8	1.247
0.09	1.36	0.2266	1.348	0.4833	1.335	3	1.241
0.0933	1.36	0.23	1.348	0.5	1.335	3.2	1.238
0.0966	1.357	0.2333	1.348	0.5166	1.332	3.4	1.231
0.1	1.357	0.2366	1.351	0.5333	1.332	3.6	1.228
0.1033	1.354	0.24	1.348	0.55	1.332	3.8	1.222
0.1066	1.357	0.2433	1.348	0.5666	1.329	4	1.216
0.11	1.357	0.2466	1.348	0.5833	1.329	4.2	1.212
0.1133	1.357	0.25	1.348	0.6	1.329	4.4	1.206
0.1166	1.354	0.2533	1.348	0.6166	1.326	4.6	1.203
0.12	1.36	0.2566	1.348	0.6333	1.326	4.8	1.2
0.1233	1.363	0.26	1.344	0.65	1.326	5	1.194
0.1266	1.36	0.2633	1.344	0.6666	1.326	5.2	1.19
0.13	1.357	0.2666	1.348	0.6833	1.322	5.4	1.187
0.1333	1.357	0.27	1.348	0.7	1.322	5.6	1.181

TABLE A.2 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft)	Elapsed Time (min)	Residual Drawdown (ft)	Elapsed Time (min)	Residual Drawdown (ft)
5.8	1.178	54	0.716	300	0.361
6	1.175	56	0.706	310	0.361
6.2	1.172	58	0.694	320	0.361
6.4	1.168	60	0.684	330	0.357
6.6	1.162	62	0.675	340	0.357
6.8	1.159	64	0.665	350	0.357
7	1.156	66	0.656	360	0.357
7.2	1.153	68	0.647	370	0.357
7.4	1.15	70	0.64	380	0.357
7.6	1.143	72	0.631	390	0.357
7.8	1.14	74	0.621	400	0.357
8	1.137	76	0.615	410	0.357
8.2	1.134	78	0.606	420	0.357
8.4	1.131	80	0.599	430	0.357
8.6	1.128	82	0.593	440	0.357
8.8	1.124	84	0.587		
9	1.121	86	0.577		
9.2	1.118	88	0.571		
9.4	1.115	90	0.565		
9.6	1.112	92	0.562		
9.8	1.109	94	0.555		
10	1.106	96	0.549		
12	1.077	98	0.543		
14	1.049	100	0.537		
16	1.024	110	0.511		
18	0.999	120	0.493		
20	0.977	130	0.471		
22	0.955	140	0.455		
24	0.936	150	0.442		
26	0.917	160	0.43		
28	0.898	170	0.42		
30	0.882	180	0.411		
32	0.864	190	0.401		
34	0.848	200	0.392		
36	0.832	210	0.389		
38	0.819	220	0.383		
40	0.804	230	0.379		
42	0.791	240	0.373		
44	0.779	250	0.37		
46	0.763	260	0.37		
48	0.75	270	0.367		
50	0.738	280	0.364		
52	0.725	290	0.364		

TABLE A.3 Slug test data for boring MW02 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.1667 ft; borehole radius = 0.4792 ft; Kz/Kr = 1).

Elapsed Time (min)	Residual Drawdown (ft) Test 2 Step 0	Test 2 Step 1	Test 2 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 2 Step 0	Test 2 Step 1	Test 2 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 2 Step 0	Test 2 Step 1	Test 2 Step 2
0	7.652	8.847	6.633	0.1366	6.834	8.413	6.765	0.2733	6.362	8.036	6.488
0.0033	7.293	8.621	7.281	0.14	6.821	8.401	6.759	0.2766	6.35	8.03	6.482
0.0066	7.457	8.954	7.218	0.1433	6.809	8.388	6.746	0.28	6.337	8.023	6.482
0.01	7.532	8.973	6.928	0.1466	6.796	8.382	6.74	0.2833	6.331	8.017	6.469
0.0133	7.319	8.785	7.054	0.15	6.79	8.376	6.733	0.2866	6.318	8.004	6.463
0.0166	7.319	8.728	7.117	0.1533	6.777	8.363	6.727	0.29	6.305	7.992	6.457
0.02	7.4	8.829	6.985	0.1566	6.765	8.35	6.714	0.2933	6.299	7.985	6.45
0.0233	7.337	8.822	6.991	0.16	6.752	8.344	6.714	0.2966	6.287	7.979	6.444
0.0266	7.281	8.759	7.054	0.1633	6.74	8.332	6.708	0.3	6.274	7.967	6.438
0.03	7.3	8.741	6.998	0.1666	6.727	8.319	6.696	0.3033	6.268	7.96	6.431
0.0333	7.281	8.759	6.972	0.17	6.714	8.319	6.689	0.3066	6.255	7.948	6.425
0.0366	7.237	8.734	6.998	0.1733	6.702	8.306	6.683	0.31	6.243	7.941	6.419
0.04	7.237	8.709	6.985	0.1766	6.689	8.294	6.683	0.3133	6.236	7.935	6.412
0.0433	7.23	8.696	6.96	0.18	6.677	8.287	6.67	0.3166	6.224	7.923	6.406
0.0466	7.205	8.696	6.966	0.1833	6.67	8.281	6.664	0.32	6.211	7.916	6.4
0.05	7.18	8.684	6.96	0.1866	6.658	8.269	6.658	0.3233	6.205	7.91	6.394
0.0533	7.18	8.671	6.941	0.19	6.645	8.262	6.652	0.3266	6.192	7.897	6.387
0.0566	7.161	8.646	6.941	0.1933	6.633	8.25	6.645	0.33	6.18	7.891	6.381
0.06	7.136	8.646	6.935	0.1966	6.62	8.243	6.639	0.3333	6.167	7.879	6.375
0.0633	7.124	8.634	6.916	0.2	6.614	8.231	6.633	0.35	6.117	7.841	6.343
0.0666	7.117	8.621	6.916	0.2033	6.601	8.225	6.626	0.3666	6.066	7.797	6.312
0.07	7.098	8.621	6.91	0.2066	6.589	8.218	6.62	0.3833	6.016	7.759	6.28
0.0733	7.086	8.602	6.897	0.21	6.576	8.206	6.614	0.4	5.966	7.715	6.255
0.0766	7.073	8.596	6.891	0.2133	6.563	8.199	6.607	0.4166	5.915	7.677	6.224
0.08	7.054	8.577	6.884	0.2166	6.551	8.187	6.601	0.4333	5.865	7.633	6.192
0.0833	7.042	8.571	6.878	0.22	6.538	8.181	6.595	0.45	5.815	7.595	6.161
0.0866	7.035	8.558	6.866	0.2233	6.532	8.168	6.589	0.4666	5.771	7.551	6.136
0.09	7.01	8.552	6.859	0.2266	6.519	8.162	6.576	0.4833	5.72	7.514	6.104
0.0933	6.998	8.539	6.853	0.23	6.507	8.155	6.57	0.5	5.67	7.476	6.073
0.0966	6.991	8.527	6.847	0.2333	6.501	8.143	6.57	0.5166	5.626	7.432	6.047
0.1	6.972	8.52	6.84	0.2366	6.482	8.137	6.557	0.5333	5.576	7.394	6.016
0.1033	6.966	8.508	6.834	0.24	6.475	8.13	6.551	0.55	5.531	7.356	5.985
0.1066	6.947	8.495	6.828	0.2433	6.457	8.118	6.545	0.5666	5.481	7.312	5.959
0.11	6.935	8.489	6.815	0.2466	6.45	8.105	6.545	0.5833	5.437	7.274	5.928
0.1133	6.922	8.476	6.809	0.25	6.444	8.099	6.538	0.6	5.393	7.237	5.896
0.1166	6.91	8.47	6.803	0.2533	6.431	8.092	6.526	0.6166	5.349	7.199	5.871
0.12	6.897	8.457	6.803	0.2566	6.419	8.08	6.519	0.6333	5.305	7.161	5.84
0.1233	6.884	8.451	6.79	0.26	6.406	8.074	6.519	0.65	5.255	7.124	5.815
0.1266	6.872	8.438	6.777	0.2633	6.394	8.067	6.507	0.6666	5.217	7.086	5.783
0.13	6.859	8.426	6.771	0.2666	6.387	8.048	6.501	0.6833	5.173	7.048	5.758
0.1333	6.847	8.42	6.771	0.27	6.375	8.042	6.494	0.7	5.129	7.01	5.727

TABLE A.3 (Cont.)

	Residual Drawdown (ft)				Residual Drawdown (ft)		
Elapsed Time (min)	Test 2 Step 0	Test 2 Step 1	Test 2 Step 2	Elapsed Time (min)	Test 2 Step 0	Test 2 Step 1	Test 2 Step 2
0.7166	5.085	6.972	5.701	4	0.686	2.001	1.869
0.7333	5.041	6.935	5.67	4.2	0.591	1.825	1.73
0.75	4.997	6.897	5.645	4.4	0.509	1.667	1.592
0.7666	4.959	6.859	5.62	4.6	0.44	1.516	1.466
0.7833	4.915	6.821	5.588	4.8	0.377	1.372	1.346
0.8	4.871	6.784	5.563	5	0.327	1.24	1.233
0.8166	4.833	6.746	5.538	5.2	0.276	1.12	1.133
0.8333	4.789	6.708	5.506	5.4	0.239	1.013	1.032
0.85	4.751	6.677	5.481	5.6	0.207	0.906	0.944
0.8666	4.707	6.639	5.456	5.8	0.176	0.818	0.862
0.8833	4.669	6.601	5.425	6	0.151	0.73	0.78
0.9	4.632	6.563	5.399	6.2	0.132	0.654	0.711
0.9166	4.594	6.532	5.374	6.4	0.113	0.585	0.642
0.9333	4.55	6.494	5.349	6.6	0.1	0.516	0.585
0.95	4.512	6.457	5.324	6.8	0.088	0.459	0.528
0.9666	4.474	6.425	5.299	7	0.075	0.409	0.472
0.9833	4.437	6.387	5.267	7.2	0.069	0.365	0.428
1	4.399	6.356	5.242	7.4	0.056	0.321	0.384
1.2	3.99	5.985	4.94	7.6	0.05	0.283	0.346
1.4	3.587	5.588	4.644	7.8	0.05	0.251	0.308
1.6	3.216	5.217	4.361	8	0.044	0.226	0.276
1.8	2.876	4.858	4.09	8.2	0.037	0.195	0.251
2	2.567	4.525	3.839	8.4	0.031	0.176	0.226
2.2	2.278	4.204	3.593	8.6	0.031	0.157	0.201
2.4	2.02	3.895	3.36	8.8	0.031	0.138	0.176
2.6	1.781	3.612	3.134	9	0.025	0.119	0.157
2.8	1.567	3.335	2.926	9.2	0.025	0.107	0.144
3	1.378	3.077	2.725	9.4	0.025	0.094	0.125
3.2	1.208	2.838	2.53	9.6	0.018	0.081	0.113
3.4	1.051	2.612	2.354	9.8	0.018	0.075	0.1
3.6	0.919	2.391	2.184	10	0.018	0.069	0.088
3.8	0.793	2.19	2.02	12		0.025	0.031

TABLE A.4 Slug test data for boring MW04 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.1667 ft; borehole radius = 0.4792 ft; Kz/Kr = 1).

Elapsed Time (min)	Residual Drawadown (ft) Slug In	Residual Drawadown (ft) Slug Out	Elapsed Time (min)	Residual Drawadown (ft) Slug In	Residual Drawadown (ft) Slug Out	Elapsed Time (min)	Residual Drawadown (ft) Slug In	Residual Drawadown (ft) Slug Out
0	0	0	0.3147	1.148	1.161	3.1297	1.053	1.063
0.005	0.009	0.002	0.3333	1.148	1.16	3.3163	1.046	1.058
0.01	0.011		0.3532	1.146	1.158	3.5147	1.041	1.051
0.015	0.013	0.006	0.3742	1.145	1.157	3.7247	1.037	1.046
0.02	0.014	0.003	0.3963	1.144	1.157	3.9463	1.029	1.039
0.025	0.859		0.4198	1.142	1.155	4.1813	1.025	1.033
0.03	1.041	0.033	0.4447	1.141	1.155	4.4295	1.017	1.027
0.035	1.157		0.4697	1.14	1.153	4.693	1.009	1.038
0.04	0.917	0.004	0.4963	1.138	1.153	4.973	1.002	1.008
0.045	1.616		0.5247	1.137	1.151	5.2697	0.995	1
0.05	1.407	0.053	0.5547	1.135	1.148	5.583	0.986	0.993
0.055	1.319	0.489	0.5863	1.134	1.148	5.9147	0.979	0.981
0.06	0.513		0.6213	1.134	1.147	6.2663	0.97	0.971
0.065	1.539	0.293	0.6578	1.13	1.146	6.6397	0.961	0.963
0.07	0.9		0.6963	1.13	1.144	7.0347	0.951	0.951
0.075	1.345	2.048	0.738	1.127	1.143	7.453	0.94	0.942
0.08	1.035		0.7813	1.126	1.141	7.8963	0.93	0.933
0.0848	1.362	0.946	0.828	1.125	1.138	8.3663	0.919	0.919
0.09	1.11	1.243	0.8763	1.123	1.136	8.8647	0.908	0.908
0.095	0.978	0.966	0.928	1.121	1.134	9.3913	0.895	0.901
0.1	1.26	1.482	0.983	1.119	1.133	9.9497	0.883	0.888
0.1058	1.149	1.081	1.0413	1.118	1.131	10.5413	0.871	0.874
0.112	1.159	1.058	1.103	1.114	1.129	11.168	0.858	0.86
0.1185	1.238	1.215	1.168	1.112	1.126	11.8313	0.843	0.846
0.1255	1.156	1.246	1.238	1.111	1.124	12.5347	0.83	0.831
0.1328	1.145	1.226	1.3113	1.108	1.121	13.2797	0.815	0.818
0.1407	1.168	1.204	1.3897	1.106	1.119	14.0697	0.8	0.802
0.149	1.178	1.193	1.473	1.104	1.115	14.9063	0.784	0.785
0.1578	1.175	1.198	1.5613	1.1	1.112	15.7913	0.766	0.769
0.167	1.164	1.198	1.6547	1.097	1.11	16.7297	0.75	0.751
0.177	1.162	1.199	1.753	1.095	1.105	17.723	0.732	0.734
0.1875	1.16	1.205	1.858	1.09	1.102	18.7763	0.716	0.717
0.1985	1.159	1.242	1.968	1.086	1.099	19.8913	0.697	0.699
0.2102	1.156	1.619	2.0847	1.084	1.094	21.073	0.678	0.681
0.2227	1.155	1.283	2.2097	1.082	1.091	22.3247	0.659	0.662
0.2358	1.154	1.122	2.3412	1.075	1.088	23.6497	0.641	0.642
0.2498	1.152	1.188	2.4813	1.073	1.082	25.0547	0.621	0.622
0.2647	1.152	1.173	2.6297	1.067	1.078	26.543	0.601	0.603
0.2803	1.151	1.164	2.7863	1.063	1.074	28.118	0.582	0.583
0.297	1.149	1.163	2.953	1.058	1.069	29.7863	0.561	0.563

TABLE A.4 (Cont.)

	Residual Drawdown (ft)			Residual Drawdown (ft)			Residual Drawdown (ft)	
Elapsed Time (min)	Slug In	Slug Out	Elapsed Time (min)	Slug In	Slug Out	Elapsed Time (min)	Slug In	Slug Out
31.5547	0.54	0.542	278.2747		0.097	678.2747		0.041
33.428	0.52	0.52	288.2747		0.094	688.2747		0.041
35.4112	0.503	0.5	298.2747		0.092	698.2747		0.04
37.513	0.478	0.48	308.2747		0.09	708.2747		0.039
39.7397	0.456	0.46	318.2747		0.088	718.2747		0.039
42.098	0.437	0.44	328.2747		0.086	728.2747		0.039
44.5963	0.416	0.419	338.2747		0.084	738.2747		0.038
47.243	0.396	0.4	348.2747		0.081	748.2747		0.038
50.0463	0.376	0.379	358.2747		0.079	758.2747		0.038
53.0147	0.356	0.361	368.2747		0.077	768.2747		0.037
56.1597	0.339	0.344	378.2747		0.076	778.2747		0.037
59.4913	0.319	0.326	388.2747		0.074	788.2747		0.036
63.0197	0.302	0.308	398.2747		0.073	798.2747		0.037
66.758	0.284	0.292	408.2747		0.071	808.2747		0.036
70.718	0.27	0.276	418.2747		0.07	818.2747		0.036
74.9113	0.254	0.262	428.2747		0.068	828.2747		0.034
79.3547	0.239	0.248	438.2747		0.066	838.2747		0.032
84.0613	0.226	0.234	448.2747		0.065			
89.0463	0.213	0.223	458.2747		0.065			
94.3263	0.199	0.211	468.2747		0.065			
99.9197	0.187	0.199	478.2747		0.063			
105.8447	0.177	0.19	488.2747		0.062			
112.1197	0.166	0.18	498.2747		0.06			
118.768	0.158	0.172	508.2747		0.06			
125.8097	0.149	0.164	518.2747		0.06			
133.268	0.142	0.157	528.2747		0.058			
141.168	0.133	0.15	538.2747		0.057			
149.5363	0.128	0.144	548.2747		0.056			
158.4013	0.121	0.138	558.2747		0.056			
167.7913	0.117	0.132	568.2747		0.054			
177.738	0.112	0.127	578.2747		0.053			
188.2747	0.106	0.125	588.2747		0.051			
198.2747	0.104	0.12	598.2747		0.05			
208.2747		0.116	608.2747		0.049			
218.2747		0.114	618.2747		0.048			
228.2747		0.109	628.2747		0.045			
238.2747		0.106	638.2747		0.044			
248.2747		0.104	648.2747		0.043			
258.2747		0.101	658.2747		0.043			
268.2747		0.099	668.2747		0.043			

TABLE A.5 Slug test data for boring MW06 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.1667 ft; borehole radius = 0.4792 ft; Kz/Kr = 1).

	Residual Drawdown (ft)			Residual Drawdown (ft)	
Elapsed Time (min)	Slug In	Slug Out	Elapsed Time (min)	Slug In	Slug Out
0			0.3147	0.861	1.535
0.005	0.002		0.3333	0.861	1.553
0.01	0.004		0.3532	0.859	1.558
0.015	0.007		0.3742	0.859	1.04
0.02	0.007		0.3963	0.857	1.031
0.025	0.007	1.113	0.4198	0.854	1.026
0.03	0.006	0.025	0.4447	0.854	1.026
0.035	0.009	0.802	0.4697	0.854	1.026
0.04	0.006	0.102	0.4963	0.852	1.024
0.045	0.009	0.588	0.5247	0.852	1.022
0.05	0.009	1.24	0.5547	0.85	1.02
0.055	0.009	1.086	0.5863	0.848	1.02
0.06	0.22	1.113	0.6213	0.848	1.018
0.065	1.471	1.071	0.6578	0.846	1.015
0.07	1.605	1.071	0.6963	0.843	1.015
0.075	0.828	1.066	0.738	0.843	1.015
0.08	1.154	1.06	0.7813	0.841	1.011
0.0848	0.231	1.058	0.828	0.841	1.009
0.09	0.817	1.058	0.8763	0.839	1.009
0.095	0.973	1.056	0.928	0.837	1.007
0.1	0.982	1.053	0.983	0.835	1.004
0.1058	0.801	1.051	1.0413	0.832	1.002
0.112	0.83	1.051	1.103	0.83	1
0.1185	0.938	1.051	1.168	0.83	0.998
0.1255	0.891	1.049	1.238	0.826	0.996
0.1328	0.865	1.051	1.3113	0.826	0.995
0.1407	0.867	1.051	1.3897	0.826	0.993
0.149	0.872	1.051	1.473	0.822	0.991
0.1578	0.872	1.049	1.5613	0.819	0.987
0.167	0.87	1.047	1.6547	0.817	0.984
0.177	0.87	1.051	1.753	0.815	0.982
0.1875	0.867	1.049	1.858	0.813	0.98
0.1985	0.865	1.055	1.968	0.811	0.976
0.2102	0.867	1.071	2.0847	0.806	0.973
0.2227	0.865	1.066	2.2097	0.804	0.971
0.2358	0.863	1.084	2.3412	0.8	0.967
0.2498	0.863	2.262	2.4813	0.8	0.965
0.2647	0.863	1.969	2.6297	0.795	0.96
0.2803	0.861	1.864	2.7863	0.791	0.958
0.297	0.861	1.857	2.953	0.789	0.954

TABLE A.5 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out	Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out
3.1297	0.784	0.949	33.428	0.491	0.663
3.3163	0.78	0.947	35.4112	0.482	0.656
3.5147	0.778	0.94	37.513	0.473	0.647
3.7247	0.771	0.936	39.7397	0.462	0.639
3.9463	0.769	0.934	42.098	0.453	0.632
4.1813	0.762	0.927	44.5963	0.444	0.623
4.4295	0.76	0.923	47.243	0.433	0.614
4.693	0.754	0.918	50.0463	0.424	0.606
4.973	0.749	0.914	53.0147	0.413	0.597
5.2697	0.743	0.907	56.1597	0.405	0.588
5.583	0.738	0.903	59.4913	0.394	0.581
5.9147	0.732	0.898	63.0197	0.383	0.573
6.2663	0.725	0.892	66.758	0.374	0.566
6.6397	0.721	0.887	70.718	0.365	0.557
7.0347	0.714	0.881	74.9113	0.354	0.551
7.453	0.707	0.874	79.3547	0.345	0.542
7.8963	0.703	0.868	84.0613	0.334	0.533
8.3663	0.696	0.859	89.0463	0.325	0.524
8.8647	0.69	0.852	94.3263	0.316	0.518
9.3913	0.683	0.848	99.9197	0.307	0.511
9.9497	0.674	0.839	105.8447	0.296	0.504
10.5413	0.666	0.834	112.1197	0.288	0.498
11.168	0.659	0.826	118.768	0.279	0.489
11.8313	0.652	0.819	125.8097	0.27	0.482
12.5347	0.643	0.81	133.268	0.259	0.473
13.2797	0.635	0.804	141.168	0.25	0.467
14.0697	0.628	0.795	149.5363	0.241	0.46
14.9063	0.619	0.786	158.4013	0.23	0.454
15.7913	0.611	0.777	167.7913	0.221	0.447
16.7297	0.602	0.768	177.738	0.215	0.441
17.723	0.593	0.762	188.2747	0.203	0.434
18.7763	0.584	0.751	198.2747	0.195	0.429
19.8913	0.574	0.744	208.2747	0.188	0.423
21.073	0.567	0.733	218.2747	0.177	
22.3247	0.558	0.724	228.2747	0.17	
23.6497	0.547	0.716	238.2747	0.162	
25.0547	0.538	0.709			
26.543	0.53	0.698			
28.118	0.519	0.692			
29.7863	0.51	0.683			
31.5547	0.5	0.674			

TABLE A.6 Slug test data for boring MW07 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.08333 ft; borehole radius = 0.3438 ft; Kz/Kr = 1).

Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out	Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out	Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out
0			0.5863	0.584	0.647	11.168	0.223	0.385
0.005	0.198	0.641	0.6213	0.582	0.646	11.8313	0.211	0.374
0.01	1.151	0.538	0.6578	0.578	0.644	12.5347	0.197	0.363
0.015	1.364	0.399	0.6963	0.575	0.641	13.2797	0.185	0.353
0.02	0.569	0.776	0.738	0.572	0.64	14.0697	0.171	0.341
0.025	0.166	1.11	0.7813	0.57	0.638	14.9063	0.159	0.33
0.03	0.559	0.917	0.828	0.567	0.635	15.7913	0.146	0.318
0.035	0.925	0.58	0.8763	0.563	0.633	16.7297	0.133	0.306
0.04	0.873	0.594	0.928	0.56	0.629	17.723	0.122	0.294
0.045	0.595	0.808	0.983	0.554	0.627	18.7763	0.107	0.282
0.05	0.513	0.859	1.0413	0.552	0.625	19.8913	0.095	0.269
0.055	0.655	0.716	1.103	0.548	0.622	21.073	0.083	0.257
0.06	0.762	0.618	1.168	0.543	0.619	22.3247	0.07	0.245
0.065	0.712	0.673	1.238	0.539	0.616	23.6497	0.058	0.233
0.07	0.613	0.761	1.3113	0.535	0.614	25.0547	0.047	0.221
0.075	0.596	0.74	1.3897	0.53	0.61	26.543	0.036	0.208
0.08	0.65	0.672	1.473	0.525	0.606	28.118	0.025	0.197
0.0848	0.687	0.654	1.5613	0.52	0.604	29.7863	0.014	0.185
0.09	0.662	0.695	1.6547	0.515	0.599	31.5547	0.003	0.174
0.095	0.625	0.717	1.753	0.511	0.597	33.428		0.162
0.1	0.622	0.693	1.858	0.501	0.593	35.4112		0.151
0.1058	0.647	0.665	1.968	0.495	0.589	37.513		0.14
0.112	0.651	0.678	2.0847	0.49	0.585	39.7397		0.13
0.1185	0.633	0.692	2.2097	0.484	0.587	42.098		0.12
0.1255	0.628	0.674	2.3412	0.476	0.582	44.5963		0.109
0.1328	0.639	0.672	2.4813	0.471	0.578	47.243		0.099
0.1407	0.634	0.68	2.6297	0.463	0.575	50.0463		0.09
0.149	0.627	0.671	2.7863	0.457	0.566	53.0147		0.083
0.1578	0.631	0.67	2.953	0.45	0.561	56.1597		0.074
0.167	0.624	0.674	3.1297	0.442	0.555	59.4913		0.066
0.177	0.621	0.671	3.3163	0.435	0.55	63.0197		0.058
0.1875	0.621	0.672	3.5147	0.427	0.544	66.758		0.052
0.1985	0.619	0.67	3.7247	0.42	0.54	70.718		0.045
0.2102	0.618	0.67	3.9463	0.412	0.533	74.9113		0.039
0.2227	0.616	0.669	4.1813	0.403	0.527	79.3547		0.033
0.2358	0.615	0.669	4.4295	0.394	0.52	84.0613		0.028
0.2498	0.611	0.668	4.693	0.405	0.513	89.0463		0.023
0.2647	0.61	0.666	4.973	0.373	0.507	94.3263		0.019
0.2803	0.609	0.666	5.2697	0.365	0.5	99.9197		0.015
0.297	0.607	0.664	5.583	0.356	0.492	105.8447		0.011
0.3147	0.606	0.663	5.9147	0.347	0.485	112.1197		0.008
0.3333	0.604	0.663	6.2663	0.338	0.477	118.768		0.005
0.3532	0.604	0.661	6.6397	0.327	0.468	125.8097		0.002
0.3742	0.6	0.659	7.0347	0.317	0.461			
0.3963	0.599	0.658	7.453	0.306	0.453			
0.4198	0.596	0.657	7.8963	0.294	0.443			
0.4447	0.595	0.656	8.3663	0.283	0.434			
0.4697	0.593	0.653	8.8647	0.271	0.425			
0.4963	0.59	0.652	9.3913	0.26	0.416			
0.5247	0.588	0.65	9.9497	0.247	0.405			
0.5547	0.586	0.648	10.5413	0.235	0.396			

TABLE A.7 Slug test data for boring MW08 (effective saturated thickness = 15 ft: length of well = 15 ft; length of screen = 15 ft; casing radius = 0.08333 ft; borehole radius = 0.3438 ft; Kz/Kr = 1).

Elapsed Time (min)	Residual Drawdown (ft) Test 6 Step 0	Test 7 Step 0	Test 7 Step 1	Elapsed Time (min)	Residual Drawdown (ft) Test 6 Step 0	Test 7 Step 0	Test 7 Step 1
0	6.248	4.901	6.75	0.1333	3.543	2.799	3.793
0.0033	5.367	4.259	5.234	0.1366	3.53	2.793	3.781
0.0066	3.429	2.774	3.523	0.14	3.517	2.78	3.768
0.01	3.832	2.957	4.309	0.1433	3.505	2.768	3.762
0.0133	4.656	3.636	5.026	0.1466	3.492	2.762	3.749
0.0166	4.373	3.548	4.573	0.15	3.48	2.749	3.737
0.02	3.889	3.158	4.139	0.1533	3.473	2.743	3.724
0.0233	3.958	3.12	4.271	0.1566	3.461	2.736	3.712
0.0266	4.134	3.259	4.416	0.16	3.448	2.724	3.699
0.03	4.065	3.246	4.309	0.1633	3.436	2.711	3.686
0.0333	3.939	3.145	4.209	0.1666	3.423	2.705	3.68
0.0366	3.933	3.114	4.215	0.17	3.41	2.699	3.668
0.04	3.958	3.133	4.227	0.1733	3.398	2.686	3.655
0.0433	3.926	3.126	4.19	0.1766	3.385	2.68	3.642
0.0466	3.889	3.095	4.158	0.18	3.373	2.667	3.63
0.05	3.876	3.076	4.146	0.1833	3.36	2.661	3.623
0.0533	3.87	3.07	4.133	0.1866	3.354	2.648	3.611
0.0566	3.851	3.057	4.114	0.19	3.341	2.642	3.598
0.06	3.826	3.038	4.095	0.1933	3.329	2.636	3.586
0.0633	3.813	3.026	4.083	0.1966	3.322	2.623	3.579
0.0666	3.801	3.013	4.064	0.2	3.31	2.617	3.567
0.07	3.788	3.001	4.051	0.2033	3.297	2.604	3.554
0.0733	3.769	2.988	4.039	0.2066	3.291	2.598	3.548
0.0766	3.756	2.975	4.02	0.21	3.278	2.592	3.535
0.08	3.744	2.969	4.007	0.2133	3.266	2.579	3.523
0.0833	3.731	2.957	3.995	0.2166	3.253	2.573	3.51
0.0866	3.712	2.944	3.976	0.22	3.247	2.56	3.504
0.09	3.706	2.931	3.963	0.2233	3.234	2.554	3.491
0.0933	3.694	2.925	3.951	0.2266	3.222	2.548	3.479
0.0966	3.675	2.913	3.938	0.23	3.209	2.535	3.472
0.1	3.662	2.9	3.925	0.2333	3.203	2.529	3.46
0.1033	3.65	2.887	3.913	0.2366	3.19	2.523	3.447
0.1066	3.637	2.881	3.894	0.24	3.184	2.51	3.441
0.11	3.624	2.869	3.888	0.2433	3.171	2.504	3.428
0.1133	3.612	2.862	3.869	0.2466	3.159	2.497	3.416
0.1166	3.599	2.85	3.856	0.25	3.146	2.491	3.41
0.12	3.587	2.837	3.844	0.2533	3.14	2.478	3.397
0.1233	3.574	2.831	3.831	0.2566	3.127	2.472	3.391
0.1266	3.561	2.818	3.819	0.26	3.121	2.466	3.378
0.13	3.549	2.812	3.806	0.2633	3.109	2.453	3.366

TABLE A.7 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 6 Step 0	Test 7 Step 0	Test 7 Step 1	Elapsed Time (min)	Residual Drawdown (ft) Test 6 Step 0	Test 7 Step 0	Test 7 Step 1
0.2666	3.102	2.447	3.359	0.7	2.077	1.629	2.327
0.27	3.096	2.441	3.347	0.7166	2.045	1.604	2.296
0.2733	3.077	2.434	3.34	0.7333	2.014	1.579	2.265
0.2766	3.071	2.422	3.328	0.75	1.989	1.554	2.233
0.28	3.058	2.416	3.322	0.7666	1.951	1.528	2.202
0.2833	3.052	2.409	3.309	0.7833	1.926	1.51	2.17
0.2866	3.039	2.403	3.303	0.8	1.894	1.484	2.139
0.29	3.027	2.39	3.29	0.8166	1.869	1.459	2.107
0.2933	3.02	2.384	3.277	0.8333	1.844	1.44	2.082
0.2966	3.014	2.378	3.271	0.85	1.812	1.415	2.051
0.3	3.002	2.372	3.259	0.8666	1.787	1.396	2.026
0.3033	2.995	2.359	3.252	0.8833	1.756	1.371	1.994
0.3066	2.983	2.353	3.24	0.9	1.731	1.352	1.969
0.31	2.976	2.346	3.233	0.9166	1.705	1.333	1.937
0.3133	2.964	2.34	3.227	0.9333	1.68	1.308	1.912
0.3166	2.958	2.334	3.215	0.95	1.655	1.289	1.887
0.32	2.945	2.321	3.202	0.9666	1.63	1.27	1.862
0.3233	2.932	2.315	3.196	0.9833	1.605	1.252	1.837
0.3266	2.926	2.309	3.183	1	1.58	1.233	1.812
0.33	2.92	2.302	3.177	1.2	1.341	1.031	1.547
0.3333	2.907	2.296	3.164	1.4	1.114	0.862	1.308
0.35	2.863	2.258	3.12	1.6	0.925	0.717	1.107
0.3666	2.819	2.22	3.076	1.8	0.774	0.591	0.937
0.3833	2.775	2.189	3.038	2	0.642	0.497	0.792
0.4	2.737	2.151	2.994	2.2	0.542	0.415	0.673
0.4166	2.693	2.12	2.95	2.4	0.453	0.346	0.572
0.4333	2.649	2.088	2.913	2.6	0.378	0.289	0.484
0.45	2.611	2.057	2.869	2.8	0.315	0.245	0.415
0.4666	2.574	2.026	2.831	3	0.265	0.201	0.352
0.4833	2.53	1.988	2.787	3.2	0.221	0.163	0.295
0.5	2.492	1.963	2.749	3.4	0.183	0.138	0.251
0.5166	2.454	1.931	2.711	3.6	0.158	0.119	0.213
0.5333	2.416	1.9	2.673	3.8	0.133	0.1	0.182
0.55	2.379	1.868	2.636	4	0.107	0.081	0.157
0.5666	2.347	1.843	2.598	4.2	0.095	0.069	0.132
0.5833	2.31	1.812	2.567	4.4	0.082	0.056	0.113
0.6	2.272	1.786	2.529	4.6	0.07	0.05	0.094
0.6166	2.24	1.755	2.491	4.8	0.057	0.044	0.081
0.6333	2.209	1.73	2.46	5	0.044	0.037	0.069
0.65	2.171	1.705	2.428	5.2	0.044	0.031	0.062
0.6666	2.14	1.679	2.39	5.4	0.038	0.025	0.05
0.6833	2.108	1.654	2.359	5.6	0.032	0.018	0.044

TABLE A.7 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 6 Step 0	Test 7 Step 0	Test 7 Step 1	Elapsed Time (min)	Residual Drawdown (ft) Test 6 Step 0	Test 7 Step 0	Test 7 Step 1
5.8	0.026	0.018	0.037	7.2	0.007	0.006	0.012
6	0.019	0.012	0.031	7.4	0.007	0.006	0.012
6.2	0.019	0.012	0.031	7.6	0.007	0.006	0.012
6.4	0.013	0.012	0.025	7.8	0.007	0.006	0.012
6.6	0.013	0.006	0.018	8	0.007	0.006	0.006
6.8	0.013	0.006	0.018	8.2	0.007	0.006	0.006
7	0.013	0.006	0.018				

TABLE A.8 Slug test data for boring MW10 (effective saturated thickness = 15 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.08333 ft; borehole radius = 0.3438 ft; Kz/Kr = 1).

	Residual Drawdown (ft)				Residual Drawdown (ft)		
Elapsed Time (min)	Test 0 Step 0	Test 0 Step 1	Test 0 Step 2	Elapsed Time (min)	Test 0 Step 0	Test 0 Step 1	Test 0 Step 2
0	4.824	4.616	3.195	0.1333	3.654	3.107	2.157
0.0033	5.113	4.107	3.572	0.1366	3.629	3.138	2.157
0.0066	2.302	1.597	1.622	0.14	3.622	3.138	2.107
0.01	2.427	1.987	0.968	0.1433	3.641	3.107	2.1
0.0133	4.622	4.025	2.27	0.1466	3.647	3.113	2.132
0.0166	4.396	3.874	3.069	0.15	3.629	3.132	2.151
0.02	2.748	2.289	2.377	0.1533	3.629	3.132	2.125
0.0233	3.019	2.239	1.396	0.1566	3.641	3.119	2.1
0.0266	4.283	3.534	1.78	0.16	3.641	3.113	2.113
0.03	4.044	3.685	2.641	0.1633	3.629	3.125	2.138
0.0333	3.056	2.692	2.591	0.1666	3.629	3.132	2.125
0.0366	3.32	2.465	1.855	0.17	3.635	3.119	2.107
0.04	4.075	3.295	1.685	0.1733	3.635	3.119	2.107
0.0433	3.842	3.534	2.264	0.1766	3.629	3.125	2.119
0.0466	3.251	2.924	2.553	0.18	3.629	3.125	2.125
0.05	3.484	2.679	2.17	0.1833	3.635	3.119	2.113
0.0533	3.93	3.176	1.805	0.1866	3.635	3.119	2.1
0.0566	3.729	3.408	2.037	0.19	3.629	3.119	2.107
0.06	3.39	3.044	2.396	0.1933	3.629	3.119	2.119
0.0633	3.578	2.83	2.308	0.1966	3.629	3.119	2.113
0.0666	3.83	3.119	1.975	0.2	3.629	3.113	2.1
0.07	3.673	3.314	1.962	0.2033	3.622	3.119	2.1
0.0733	3.478	3.1	2.232	0.2066	3.629	3.119	2.107
0.0766	3.622	2.937	2.32	0.21	3.629	3.119	2.107
0.08	3.761	3.1	2.113	0.2133	3.622	3.113	2.1
0.0833	3.641	3.245	1.987	0.2166	3.622	3.119	2.094
0.0866	3.541	3.125	2.119	0.22	3.622	3.119	2.1
0.09	3.641	3.006	2.264	0.2233	3.622	3.119	2.1
0.0933	3.717	3.094	2.188	0.2266	3.622	3.113	2.1
0.0966	3.635	3.201	2.05	0.23	3.622	3.113	2.094
0.1	3.578	3.138	2.069	0.2333	3.622	3.113	2.094
0.1033	3.647	3.05	2.195	0.2366	3.622	3.113	2.094
0.1066	3.685	3.094	2.207	0.24	3.622	3.113	2.094
0.11	3.629	3.17	2.107	0.2433	3.616	3.113	2.088
0.1133	3.603	3.138	2.069	0.2466	3.622	3.113	2.088
0.1166	3.647	3.081	2.138	0.25	3.616	3.113	2.094
0.12	3.666	3.1	2.188	0.2533	3.616	3.113	2.088
0.1233	3.629	3.151	2.144	0.2566	3.616	3.113	2.088
0.1266	3.616	3.138	2.088	0.26	3.616	3.113	2.088
0.13	3.647	3.1	2.107	0.2633	3.616	3.113	2.088

TABLE A.8 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 0 Step 0	Test 0 Step 1	Test 0 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 0 Step 0	Test 0 Step 1	Test 0 Step 2
0.2666	3.616	3.113	2.088	0.7	3.528	3.031	1.949
0.27	3.616	3.107	2.081	0.7166	3.528	3.031	1.949
0.2733	3.616	3.107	2.081	0.7333	3.522	3.025	1.943
0.2766	3.61	3.107	2.081	0.75	3.515	3.019	1.937
0.28	3.61	3.107	2.081	0.7666	3.515	3.019	1.93
0.2833	3.61	3.107	2.081	0.7833	3.509	3.012	1.924
0.2866	3.61	3.107	2.075	0.8	3.509	3.012	1.924
0.29	3.61	3.107	2.075	0.8166	3.503	3.006	1.918
0.2933	3.61	3.107	2.075	0.8333	3.503	3.006	1.912
0.2966	3.61	3.107	2.075	0.85	3.497	3	1.905
0.3	3.61	3.107	2.075	0.8666	3.497	2.993	1.899
0.3033	3.61	3.1	2.075	0.8833	3.49	2.993	1.899
0.3066	3.603	3.1	2.069	0.9	3.49	2.993	1.893
0.31	3.603	3.1	2.069	0.9166	3.484	2.987	1.893
0.3133	3.603	3.1	2.069	0.9333	3.484	2.987	1.886
0.3166	3.603	3.1	2.069	0.95	3.478	2.981	1.88
0.32	3.603	3.1	2.063	0.9666	3.478	2.975	1.874
0.3233	3.603	3.1	2.069	0.9833	3.471	2.975	1.868
0.3266	3.603	3.1	2.069	1	3.471	2.968	1.861
0.33	3.603	3.1	2.063	1.2	3.44	2.937	1.817
0.3333	3.603	3.094	2.063	1.4	3.408	2.899	1.754
0.35	3.597	3.094	2.056	1.6	3.371	2.861	1.704
0.3666	3.597	3.094	2.056	1.8	3.333	2.83	1.647
0.3833	3.591	3.088	2.05	2	3.302	2.792	1.597
0.4	3.591	3.088	2.044	2.2	3.264	2.754	1.553
0.4166	3.585	3.081	2.037	2.4	3.232	2.673	1.503
0.4333	3.578	3.081	2.031	2.6	3.201	2.597	1.452
0.45	3.578	3.075	2.031	2.8	3.17	2.515	1.408
0.4666	3.578	3.075	2.025	3	3.132	2.44	1.371
0.4833	3.572	3.075	2.019	3.2	3.1	2.364	1.327
0.5	3.566	3.069	2.012	3.4	3.063	2.295	1.283
0.5166	3.566	3.069	2.006	3.6	3.031	2.226	1.245
0.5333	3.566	3.063	2	3.8	2.993	2.157	1.207
0.55	3.559	3.063	2	4	2.956	2.094	1.169
0.5666	3.553	3.056	1.993	4.2	2.918	2.031	1.138
0.5833	3.553	3.05	1.987	4.4	2.88	1.975	1.1
0.6	3.547	3.05	1.981	4.6	2.842	1.912	1.069
0.6166	3.547	3.044	1.981	4.8	2.811	1.855	1.037
0.6333	3.541	3.044	1.975	5	2.78	1.798	1.006
0.65	3.541	3.044	1.968	5.2	2.717	1.742	0.974
0.6666	3.534	3.037	1.962	5.4	2.641	1.691	0.949
0.6833	3.534	3.037	1.956	5.6	2.566	1.641	0.912

TABLE A.8 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 0 Step 0	Test 0 Step 1	Test 0 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 0 Step 0	Test 0 Step 1	Test 0 Step 2
5.8	2.49	1.591	0.886	9.2	1.522	0.93	0.522
6	2.421	1.541	0.861	9.4	1.478	0.905	0.503
6.2	2.352	1.496	0.836	9.6	1.434	0.874	0.49
6.4	2.283	1.446	0.811	9.8	1.39	0.849	0.471
6.6	2.214	1.402	0.786	10	1.352	0.817	0.459
6.8	2.151	1.358	0.761	12	1.012	0.591	0.333
7	2.094	1.32	0.735	14	0.761	0.427	0.239
7.2	2.031	1.276	0.717	16	0.566	0.301	0.169
7.4	1.975	1.239	0.691	18	0.427	0.213	0.119
7.6	1.918	1.201	0.666	20	0.32	0.15	0.075
7.8	1.861	1.163	0.647	22	0.239	0.1	0.05
8	1.811	1.125	0.628	24	0.182	0.069	0.025
8.2	1.754	1.094	0.61	26	0.132		0.012
8.4	1.704	1.056	0.591	28	0.1		
8.6	1.66	1.025	0.572	30	0.069		
8.8	1.61	0.993	0.553	32	0.05		
9	1.566	0.962	0.54				

TABLE A.9 Slug test data for boring SB01 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.04167 ft; borehole radius = 0.05469 ft; Kz/Kr = 1).

Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out	Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out	Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out
0			0.297	0.409	0.445	2.7863	0.368	0.403
0.005	0.004		0.3147	0.407	0.443	2.953	0.367	0.401
0.01	0.006		0.3333	0.407	0.443	3.1297	0.37	0.401
0.015	0.008		0.3532	0.405	0.443	3.3163	0.368	0.401
0.02	0.008		0.3742	0.402	0.441	3.5147	0.368	0.401
0.025	0.008		0.3963	0.402	0.439	3.7247	0.368	0.401
0.03	0.008		0.4198	0.4	0.437	3.9463	0.365	0.401
0.035	0.01		0.4447	0.4	0.437	4.1813	0.365	0.399
0.04	0.01		0.4697	0.398	0.434	4.4295	0.365	0.399
0.045	0.01		0.4963	0.398	0.434	4.693	0.365	0.399
0.05	0.01		0.5247	0.396	0.432	4.973	0.365	0.397
0.055	0.01		0.5547	0.394	0.43	5.2697	0.365	0.399
0.06	0.01		0.5863	0.394	0.43	5.583	0.363	0.397
0.065	0.01	0.679	0.6213	0.394	0.428	5.9147	0.363	0.399
0.07	0.01	0.215	0.6578	0.391	0.426	6.2663	0.363	0.397
0.075	0.01	0.298	0.6963	0.389	0.426	6.6397	0.363	0.397
0.08	0.012	0.371	0.738	0.389	0.426	7.0347	0.361	0.397
0.0848	0.01	0.433	0.7813	0.387	0.423	7.453	0.361	0.397
0.09	0.01	0.486	0.828	0.387	0.423	7.8963	0.361	0.397
0.095	0.012	0.481	0.8763	0.385	0.421	8.3663	0.359	0.394
0.1	0.014	0.472	0.928	0.385	0.419	8.8647	0.359	0.394
0.1058	1.293	0.441	0.983	0.383	0.419	9.3913	0.361	0.394
0.112		0.472	1.0413	0.383	0.419	9.9497	0.359	0.394
0.1185	0.164	0.444	1.103	0.38	0.417	10.5413	0.357	0.392
0.1255	0.512	0.472	1.168	0.381	0.414	11.168	0.357	0.392
0.1328	0.444	0.461	1.238	0.378	0.414	11.8313	0.357	0.392
0.1407	0.417	0.457	1.3113	0.378	0.412	12.5347	0.354	0.392
0.149	0.422	0.455	1.3897	0.376	0.412	13.2797	0.352	0.392
0.1578	0.424	0.459	1.473	0.374	0.41	14.0697	0.352	0.392
0.167	0.422	0.468	1.5613	0.374	0.41	14.9063	0.352	0.392
0.177	0.422	0.459	1.6547	0.374	0.41	15.7913	0.352	0.392
0.1875	0.418	0.457	1.753	0.374	0.408	16.7297	0.35	0.39
0.1985	0.418	0.454	1.858	0.372	0.408	17.723	0.35	0.392
0.2102	0.415	0.452	1.968	0.372	0.405	18.7763	0.35	0.392
0.2227	0.415	0.452	2.0847	0.372	0.405	19.8913	0.346	0.392
0.2358	0.415	0.45	2.2097	0.37	0.403	21.073	0.346	0.392
0.2498	0.413	0.45	2.3412	0.37	0.405	22.3247	0.346	0.39
0.2647	0.411	0.445	2.4813	0.37	0.403	23.6497	0.343	0.39
0.2803	0.411	0.445	2.6297	0.367	0.401	25.0547	0.341	0.39

TABLE A.9 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out	Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out	Elapsed Time (min)	Residual Drawdown (ft) Slug In	Residual Drawdown (ft) Slug Out
26.543	0.341	0.388	258.2747		0.364	668.2747		0.357
28.118	0.339	0.39	268.2747		0.364	678.2747		0.357
29.7863	0.339	0.388	278.2747		0.364	688.2747		0.355
31.5547	0.337	0.388	288.2747		0.361	698.2747		0.355
33.428	0.335	0.388	298.2747		0.361	708.2747		0.357
35.4112	0.332	0.386	308.2747		0.361	718.2747		0.355
37.513	0.33	0.388	318.2747		0.361	728.2747		0.355
39.7397	0.328	0.388	328.2747		0.359	738.2747		0.355
42.098	0.326	0.388	338.2747		0.359	748.2747		0.353
44.5963	0.324	0.386	348.2747		0.361	758.2747		0.355
47.243	0.319	0.386	358.2747		0.361	768.2747		0.355
50.0463	0.319	0.383	368.2747		0.361	778.2747		0.355
53.0147	0.317	0.383	378.2747		0.361	788.2747		0.353
56.1597	0.313	0.383	388.2747		0.361	798.2747		0.35
59.4913	0.308	0.383	398.2747		0.361	808.2747		0.35
63.0197	0.308	0.379	408.2747		0.361	818.2747		0.353
66.758	0.304	0.381	418.2747		0.361	828.2747		0.348
70.718	0.302	0.381	428.2747		0.361	838.2747		0.35
74.9113	0.297	0.381	438.2747		0.361	848.2747		0.348
79.3547	0.295	0.379	448.2747		0.361	858.2747		0.348
84.0613	0.291	0.379	458.2747		0.359	868.2747		0.348
89.0463	0.286	0.377	468.2747		0.359	878.2747		0.348
94.3263	0.282	0.379	478.2747		0.359	888.2747		0.348
99.9197	0.277	0.375	488.2747		0.359	898.2747		0.346
105.8447	0.273	0.375	498.2747		0.361	908.2747		0.346
112.1197	0.269	0.375	508.2747		0.361	918.2747		0.346
118.768	0.262	0.375	518.2747		0.361	928.2747		0.346
125.8097	0.258	0.375	528.2747		0.361	938.2747		0.346
133.268	0.253	0.372	538.2747		0.361	948.2747		0.344
141.168	0.249	0.372	548.2747		0.361	958.2747		0.344
149.5363	0.24	0.37	558.2747		0.359	968.2747		0.344
158.4013	0.236	0.37	568.2747		0.359	978.2747		0.344
167.7913	0.229	0.368	578.2747		0.359	988.2747		0.344
177.738	0.222	0.37	588.2747		0.359	998.2747		0.342
188.2747	0.216	0.368	598.2747		0.359	1008.2747		0.344
198.2747	0.209	0.368	608.2747		0.359	1018.2747		0.344
208.2747	0.205	0.368	618.2747		0.359	1028.2747		0.344
218.2747	0.198	0.368	628.2747		0.359	1038.2747		0.342
228.2747	0.192	0.366	638.2747		0.357	1048.2747		0.342
238.2747	0.189	0.366	648.2747		0.357	1058.2747		0.342
248.2747		0.366	658.2747		0.357	1068.2747		0.342

TABLE A.9 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Slug In	Slug Out
1078.2747		0.342
1088.2747		0.342
1098.2747		0.339
1108.2747		0.342
1118.2747		0.339
1128.2747		0.339
1138.2747		0.339
1148.2747		0.337
1158.2747		0.337
1168.2747		0.339

TABLE A.10 Slug test data for boring SB04 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.04167 ft; borehole radius = 0.05469 ft; Kz/Kr = 1).

	Residual Drawdown (ft)				Residual Drawdown (ft)		
Elapsed Time (min)	Test 1 Step 0	Test 1 Step 1	Test 1 Step 2	Elapsed Time (min)	Test 1 Step 0	Test 1 Step 1	Test 1 Step 2
0	6.274	5.858	6.601	0.1333	0.195	0.686	0.868
0.0033	7.129	6.947	7.236	0.1366	0.176	0.648	0.824
0.0066	6.771	6.827	6.897	0.14	0.163	0.61	0.78
0.01	6.324	6.374	6.425	0.1433	0.151	0.579	0.742
0.0133	5.701	5.682	5.871	0.1466	0.144	0.547	0.704
0.0166	5.16	5.173	5.468	0.15	0.132	0.516	0.667
0.02	4.694	4.839	5.154	0.1533	0.125	0.49	0.635
0.0233	4.241	4.543	4.864	0.1566	0.119	0.459	0.604
0.0266	3.857	4.273	4.631	0.16	0.113	0.434	0.572
0.03	3.511	4.027	4.399	0.1633	0.107	0.415	0.541
0.0333	3.197	3.801	4.178	0.1666	0.1	0.39	0.516
0.0366	2.913	3.587	3.971	0.17	0.094	0.371	0.484
0.04	2.649	3.385	3.776	0.1733	0.088	0.352	0.465
0.0433	2.416	3.203	3.581	0.1766	0.088	0.333	0.44
0.0466	2.202	3.02	3.404	0.18	0.081	0.321	0.415
0.05	2.007	2.857	3.234	0.1833	0.075	0.302	0.396
0.0533	1.825	2.7	3.071	0.1866	0.075	0.289	0.377
0.0566	1.661	2.549	2.92	0.19	0.075	0.27	0.358
0.06	1.51	2.41	2.775	0.1933	0.069	0.258	0.34
0.0633	1.372	2.278	2.637	0.1966	0.069	0.245	0.327
0.0666	1.246	2.152	2.498	0.2	0.069	0.239	0.308
0.07	1.132	2.032	2.372	0.2033	0.063	0.226	0.295
0.0733	1.025	1.919	2.253	0.2066	0.063	0.214	0.283
0.0766	0.931	1.812	2.139	0.21	0.063	0.207	0.27
0.08	0.843	1.711	2.032	0.2133	0.056	0.195	0.258
0.0833	0.767	1.617	1.925	0.2166	0.056	0.188	0.245
0.0866	0.692	1.529	1.831	0.22	0.056	0.176	0.232
0.09	0.629	1.441	1.737	0.2233	0.056	0.17	0.22
0.0933	0.572	1.359	1.642	0.2266	0.05	0.163	0.214
0.0966	0.516	1.284	1.56	0.23	0.05	0.157	0.201
0.1	0.472	1.214	1.479	0.2333	0.05	0.151	0.195
0.1033	0.428	1.145	1.403	0.2366	0.05	0.144	0.188
0.1066	0.39	1.082	1.334	0.24	0.05	0.138	0.176
0.11	0.352	1.025	1.265	0.2433	0.05	0.132	0.17
0.1133	0.321	0.963	1.195	0.2466	0.05	0.125	0.163
0.1166	0.295	0.912	1.132	0.25	0.044	0.125	0.157
0.12	0.27	0.862	1.076	0.2533	0.044	0.119	0.151
0.1233	0.245	0.811	1.019	0.2566	0.044	0.113	0.144
0.1266	0.226	0.767	0.969	0.26	0.044	0.113	0.138
0.13	0.207	0.723	0.918	0.2633	0.044	0.107	0.138

TABLE A.10 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 1 Step 0	Test 1 Step 1	Test 1 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 1 Step 0	Test 1 Step 1	Test 1 Step 2
0.2666	0.044	0.107	0.132	0.7	0.018	0.025	0.031
0.27	0.037	0.1	0.125	0.7166	0.018	0.025	0.031
0.2733	0.044	0.1	0.119	0.7333	0.018	0.031	0.025
0.2766	0.037	0.094	0.119	0.75	0.018	0.031	0.025
0.28	0.037	0.094	0.113	0.7666	0.012	0.025	0.025
0.2833	0.037	0.088	0.107	0.7833	0.012	0.031	0.025
0.2866	0.037	0.088	0.107	0.8	0.018	0.031	0.025
0.29	0.037	0.081	0.1	0.8166	0.012	0.031	0.025
0.2933	0.037	0.081	0.1	0.8333	0.018	0.031	0.025
0.2966	0.037	0.081	0.094	0.85	0.012	0.031	0.025
0.3	0.037	0.075	0.094	0.8666	0.012	0.031	0.025
0.3033	0.037	0.075	0.088	0.8833	0.012	0.031	0.025
0.3066	0.031	0.075	0.088	0.9	0.012	0.031	0.025
0.31	0.037	0.075	0.088	0.9166	0.012	0.031	0.025
0.3133	0.037	0.069	0.088	0.9333	0.012	0.031	0.025
0.3166	0.031	0.069	0.081	0.95	0.012	0.025	0.025
0.32	0.031	0.069	0.081	0.9666	0.012	0.031	0.025
0.3233	0.031	0.069	0.075	0.9833	0.012	0.031	0.025
0.3266	0.031	0.069	0.075	1	0.012	0.031	0.025
0.33	0.031	0.063	0.075	1.2	0.012	0.025	0.025
0.3333	0.031	0.063	0.069	1.4	0.012	0.025	0.025
0.35	0.031	0.056	0.063	1.6	0.012	0.025	0.018
0.3666	0.031	0.05	0.056	1.8	0.012	0.025	0.025
0.3833	0.025	0.05	0.05	2	0.012	0.025	0.025
0.4	0.025	0.05	0.05	2.2	0.012	0.025	0.025
0.4166	0.025	0.044	0.044	2.4	0.012	0.025	0.025
0.4333	0.025	0.044	0.044	2.6	0.012	0.025	0.025
0.45	0.025	0.037	0.044	2.8	0.012	0.025	0.025
0.4666	0.025	0.037	0.037	3	0.012	0.025	0.018
0.4833	0.025	0.037	0.037	3.2	0.012	0.025	0.025
0.5	0.018	0.044	0.037	3.4	0.012	0.025	0.018
0.5166	0.018	0.037	0.031	3.6	0.012	0.025	0.018
0.5333	0.018	0.037	0.031	3.8	0.012	0.025	0.025
0.55	0.018	0.037	0.037	4	0.012	0.025	0.018
0.5666	0.018	0.037	0.031	4.2	0.012	0.025	0.025
0.5833	0.018	0.037	0.031	4.4	0.012	0.025	0.025
0.6	0.018	0.037	0.031	4.6	0.012	0.025	0.025
0.6166	0.018	0.031	0.031	4.8	0.012	0.025	0.018
0.6333	0.018	0.031	0.031	5	0.012	0.025	0.018
0.65	0.018	0.031	0.031	5.2	0.012	0.025	0.018
0.6666	0.018	0.031	0.031	5.4	0.012	0.025	0.025
0.6833	0.018	0.031	0.025	5.6	0.012	0.025	0.025

TABLE A.10 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 1 Step 0	Test 1 Step 1	Test 1 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 1 Step 0	Test 1 Step 1	Test 1 Step 2
5.8	0.012	0.025	0.025	8	0.006	0.025	0.025
6	0.012	0.025	0.025	8.2	0.006	0.025	0.025
6.2	0.006	0.025	0.018	8.4	0.006	0.025	0.025
6.4	0.012	0.025	0.025	8.6	0.012	0.025	0.025
6.6	0.012	0.025	0.025	8.8	0.006	0.025	0.025
6.8	0.012	0.025	0.025	9	0.006	0.025	0.025
7	0.012	0.025	0.018	9.2	0.006	0.025	0.025
7.2	0.012	0.025	0.025	9.4	0.012	0.025	0.025
7.4	0.006	0.025	0.025	9.6	0.006	0.025	0.025
7.6	0.006	0.025	0.025	9.8	0.006	0.025	0.025
7.8	0.006	0.025	0.025	10	0.006	0.025	0.025

TABLE A.11 Slug test data for boring SB05 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.04167 ft; borehole radius = 0.05469 ft; Kz/Kr = 1).

	Residual Drawdown (ft)				Residual Drawdown (ft)		
Elapsed Time (min)	Test 5 Step 0	Test 5 Step 1	Test 5 Step 2	Elapsed Time (min)	Test 5 Step 0	Test 5 Step 1	Test 5 Step 2
0	3.896	4.248	4.909	0.1333	0.616	0.61	0.938
0.0033	4.613	4.657	6.104	0.1366	0.591	0.585	0.906
0.0066	4.657	4.481	5.79	0.14	0.566	0.566	0.868
0.01	4.342	4.154	5.299	0.1433	0.547	0.541	0.837
0.0133	3.959	3.852	4.871	0.1466	0.528	0.522	0.812
0.0166	3.625	3.594	4.537	0.15	0.509	0.503	0.78
0.02	3.361	3.367	4.273	0.1533	0.491	0.484	0.755
0.0233	3.134	3.159	4.04	0.1566	0.478	0.465	0.723
0.0266	2.939	2.97	3.839	0.16	0.459	0.453	0.698
0.03	2.763	2.794	3.656	0.1633	0.447	0.434	0.679
0.0333	2.612	2.643	3.487	0.1666	0.434	0.421	0.654
0.0366	2.473	2.498	3.329	0.17	0.421	0.409	0.635
0.04	2.347	2.366	3.178	0.1733	0.403	0.396	0.616
0.0433	2.228	2.247	3.04	0.1766	0.396	0.384	0.598
0.0466	2.114	2.133	2.901	0.18	0.384	0.371	0.579
0.05	2.008	2.026	2.769	0.1833	0.371	0.358	0.56
0.0533	1.901	1.926	2.643	0.1866	0.365	0.352	0.547
0.0566	1.806	1.825	2.524	0.19	0.352	0.34	0.528
0.06	1.712	1.737	2.41	0.1933	0.346	0.333	0.516
0.0633	1.63	1.649	2.303	0.1966	0.333	0.321	0.503
0.0666	1.548	1.567	2.203	0.2	0.327	0.314	0.491
0.07	1.473	1.485	2.102	0.2033	0.321	0.308	0.478
0.0733	1.397	1.416	2.008	0.2066	0.314	0.302	0.465
0.0766	1.328	1.34	1.919	0.21	0.308	0.289	0.453
0.08	1.265	1.277	1.838	0.2133	0.302	0.283	0.44
0.0833	1.202	1.214	1.756	0.2166	0.295	0.277	0.434
0.0866	1.145	1.158	1.68	0.22	0.289	0.27	0.421
0.09	1.089	1.101	1.611	0.2233	0.283	0.27	0.415
0.0933	1.038	1.044	1.542	0.2266	0.277	0.264	0.403
0.0966	0.994	1	1.479	0.23	0.277	0.258	0.396
0.1	0.944	0.95	1.416	0.2333	0.27	0.251	0.39
0.1033	0.906	0.906	1.353	0.2366	0.264	0.251	0.377
0.1066	0.862	0.868	1.296	0.24	0.264	0.245	0.377
0.11	0.824	0.824	1.246	0.2433	0.258	0.239	0.365
0.1133	0.786	0.793	1.196	0.2466	0.251	0.239	0.358
0.1166	0.755	0.755	1.145	0.25	0.251	0.233	0.352
0.12	0.723	0.723	1.101	0.2533	0.245	0.226	0.346
0.1233	0.692	0.692	1.057	0.2566	0.245	0.226	0.34
0.1266	0.667	0.667	1.013	0.26	0.239	0.22	0.333
0.13	0.642	0.635	0.975	0.2633	0.239	0.22	0.333

TABLE A.11 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 5 Step 0	Test 5 Step 1	Test 5 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 5 Step 0	Test 5 Step 1	Test 5 Step 2
0.2666	0.233	0.214	0.327	0.7	0.125	0.107	0.163
0.27	0.233	0.214	0.321	0.7166	0.125	0.107	0.163
0.2733	0.226	0.207	0.314	0.7333	0.119	0.107	0.157
0.2766	0.226	0.207	0.308	0.75	0.119	0.107	0.157
0.28	0.22	0.207	0.308	0.7666	0.119	0.107	0.157
0.2833	0.22	0.201	0.302	0.7833	0.119	0.101	0.151
0.2866	0.22	0.201	0.302	0.8	0.113	0.101	0.151
0.29	0.214	0.201	0.295	0.8166	0.113	0.101	0.151
0.2933	0.214	0.195	0.289	0.8333	0.113	0.101	0.151
0.2966	0.214	0.195	0.289	0.85	0.113	0.101	0.144
0.3	0.214	0.195	0.283	0.8666	0.113	0.094	0.144
0.3033	0.207	0.188	0.283	0.8833	0.113	0.094	0.144
0.3066	0.207	0.188	0.277	0.9	0.107	0.094	0.144
0.31	0.207	0.188	0.277	0.9166	0.107	0.094	0.144
0.3133	0.207	0.182	0.27	0.9333	0.107	0.094	0.138
0.3166	0.201	0.182	0.27	0.95	0.107	0.094	0.138
0.32	0.201	0.182	0.27	0.9666	0.107	0.088	0.138
0.3233	0.201	0.182	0.264	0.9833	0.107	0.088	0.138
0.3266	0.201	0.176	0.264	1	0.107	0.088	0.138
0.33	0.195	0.176	0.258	1.2	0.094	0.081	0.125
0.3333	0.195	0.176	0.258	1.4	0.088	0.075	0.113
0.35	0.188	0.17	0.245	1.6	0.081	0.069	0.107
0.3666	0.182	0.163	0.239	1.8	0.075	0.063	0.101
0.3833	0.176	0.157	0.233	2	0.075	0.063	0.094
0.4	0.17	0.151	0.226	2.2	0.069	0.063	0.094
0.4166	0.17	0.151	0.22	2.4	0.069	0.056	0.088
0.4333	0.163	0.144	0.214	2.6	0.063	0.056	0.088
0.45	0.157	0.138	0.207	2.8	0.063	0.056	0.081
0.4666	0.157	0.138	0.201	3	0.063	0.056	0.081
0.4833	0.151	0.138	0.201	3.2	0.056	0.05	0.081
0.5	0.151	0.132	0.195	3.4	0.056	0.05	0.075
0.5166	0.151	0.132	0.188	3.6	0.056	0.05	0.075
0.5333	0.144	0.125	0.188	3.8	0.056	0.05	0.069
0.55	0.144	0.125	0.182	4	0.05	0.044	0.069
0.5666	0.144	0.125	0.182	4.2	0.05	0.044	0.069
0.5833	0.138	0.119	0.176	4.4	0.05	0.044	0.069
0.6	0.138	0.119	0.176	4.6	0.05	0.044	0.063
0.6166	0.132	0.119	0.176	4.8	0.044	0.044	0.063
0.6333	0.132	0.119	0.17	5	0.044	0.044	0.063
0.65	0.132	0.113	0.17	5.2	0.044	0.044	0.063
0.6666	0.125	0.113	0.163	5.4	0.044	0.044	0.063
0.6833	0.125	0.113	0.163	5.6	0.044	0.044	0.063

TABLE A.11 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 5 Step 0	Test 5 Step 1	Test 5 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 5 Step 0	Test 5 Step 1	Test 5 Step 2
5.8	0.044	0.044	0.056	8	0.037	0.037	0.05
6	0.044	0.044	0.056	8.2	0.037	0.037	0.05
6.2	0.044	0.037	0.056	8.4	0.037	0.031	0.05
6.4	0.044	0.037	0.056	8.6	0.037	0.037	0.05
6.6	0.037	0.037	0.056	8.8	0.037	0.031	0.05
6.8	0.037	0.037	0.056	9	0.037	0.031	0.05
7	0.037	0.037	0.056	9.2	0.037	0.037	0.05
7.2	0.037	0.037	0.056	9.4	0.031	0.031	0.05
7.4	0.037	0.037	0.05	9.6	0.031	0.031	0.044
7.6	0.037	0.037	0.05	9.8	0.031	0.037	0.05
7.8	0.037	0.037	0.05	10	0.031	0.031	0.044

TABLE A.12 Slug test data for boring SB07R (effective saturated thickness = 15 ft: length of well = 15 ft; length of screen = 15 ft; casing radius = 0.08333 ft; borehole radius = 0.3438 ft; Kz/Kr = 1).

	Residual Drawdown (ft)			Residual Drawdown (ft)	
Elapsed Time (min)	Test 4 Step 0	Test 4 Step 1	Elapsed Time (min)	Test 4 Step 0	Test 4 Step 1
0	4.255	4.097	0.13	3.298	2.927
0.0033	5.545	4.903	0.1333	3.292	2.92
0.0066	4.324	3.638	0.1366	3.292	2.92
0.01	3.021	2.631	0.14	3.285	2.914
0.0133	3.109	2.839	0.1433	3.285	2.914
0.0166	3.739	3.361	0.1466	3.279	2.908
0.02	3.896	3.437	0.15	3.279	2.908
0.0233	3.625	3.191	0.1533	3.273	2.901
0.0266	3.411	3.027	0.1566	3.273	2.901
0.03	3.43	3.053	0.16	3.267	2.901
0.0333	3.512	3.122	0.1633	3.26	2.895
0.0366	3.518	3.122	0.1666	3.26	2.895
0.04	3.462	3.078	0.17	3.26	2.889
0.0433	3.424	3.04	0.1733	3.254	2.889
0.0466	3.418	3.04	0.1766	3.254	2.883
0.05	3.424	3.04	0.18	3.248	2.883
0.0533	3.418	3.034	0.1833	3.248	2.883
0.0566	3.405	3.021	0.1866	3.248	2.883
0.06	3.392	3.015	0.19	3.241	2.883
0.0633	3.386	3.008	0.1933	3.235	2.876
0.0666	3.38	3.002	0.1966	3.235	2.876
0.07	3.374	2.996	0.2	3.235	2.87
0.0733	3.367	2.99	0.2033	3.229	2.87
0.0766	3.361	2.983	0.2066	3.229	2.87
0.08	3.355	2.977	0.21	3.229	2.864
0.0833	3.355	2.977	0.2133	3.222	2.864
0.0866	3.348	2.971	0.2166	3.222	2.864
0.09	3.342	2.964	0.22	3.216	2.857
0.0933	3.336	2.964	0.2233	3.216	2.857
0.0966	3.329	2.958	0.2266	3.216	2.857
0.1	3.329	2.952	0.23	3.21	2.851
0.1033	3.323	2.952	0.2333	3.21	2.851
0.1066	3.317	2.946	0.2366	3.204	2.851
0.11	3.317	2.946	0.24	3.204	2.845
0.1133	3.311	2.939	0.2433	3.204	2.845
0.1166	3.311	2.939	0.2466	3.204	2.845
0.12	3.304	2.933	0.25	3.197	2.839
0.1233	3.304	2.927	0.2533	3.197	2.839
0.1266	3.298	2.927	0.2566	3.197	2.839

TABLE A.12 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 4 Step 0	Residual Drawdown (ft) Test 4 Step 1	Elapsed Time (min)	Residual Drawdown (ft) Test 4 Step 0	Residual Drawdown (ft) Test 4 Step 1
0.26	3.191	2.832	0.65	3.002	2.669
0.2633	3.191	2.832	0.6666	2.996	2.662
0.2666	3.191	2.832	0.6833	2.99	2.656
0.27	3.185	2.832	0.7	2.983	2.65
0.2733	3.185	2.826	0.7166	2.977	2.643
0.2766	3.185	2.826	0.7333	2.971	2.637
0.28	3.178	2.826	0.75	2.964	2.637
0.2833	3.178	2.826	0.7666	2.958	2.631
0.2866	3.178	2.82	0.7833	2.952	2.625
0.29	3.172	2.82	0.8	2.946	2.618
0.2933	3.172	2.82	0.8166	2.946	2.618
0.2966	3.172	2.82	0.8333	2.939	2.612
0.3	3.166	2.813	0.85	2.933	2.606
0.3033	3.166	2.813	0.8666	2.927	2.599
0.3066	3.166	2.813	0.8833	2.92	2.593
0.31	3.166	2.807	0.9	2.914	2.587
0.3133	3.16	2.807	0.9166	2.908	2.587
0.3166	3.16	2.807	0.9333	2.901	2.58
0.32	3.16	2.807	0.95	2.895	2.574
0.3233	3.153	2.801	0.9666	2.889	2.568
0.3266	3.153	2.801	0.9833	2.889	2.568
0.33	3.153	2.801	1	2.883	2.562
0.3333	3.153	2.794	1.2	2.82	2.505
0.35	3.141	2.788	1.4	2.769	2.455
0.3666	3.134	2.782	1.6	2.713	2.417
0.3833	3.122	2.776	1.8	2.669	2.366
0.4	3.115	2.763	2	2.625	2.329
0.4166	3.109	2.757	2.2	2.58	2.297
0.4333	3.097	2.75	2.4	2.536	2.253
0.45	3.09	2.744	2.6	2.499	2.222
0.4666	3.084	2.738	2.8	2.461	2.184
0.4833	3.071	2.732	3	2.423	2.152
0.5	3.065	2.725	3.2	2.385	2.121
0.5166	3.059	2.719	3.4	2.354	2.09
0.5333	3.053	2.713	3.6	2.316	2.058
0.55	3.046	2.7	3.8	2.285	2.026
0.5666	3.04	2.694	4	2.253	1.995
0.5833	3.034	2.694	4.2	2.215	1.97
0.6	3.021	2.687	4.4	2.184	1.938
0.6166	3.015	2.681	4.6	2.159	1.913
0.6333	3.008	2.675	4.8	2.127	1.888

TABLE A.12 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 4 Step 0	Residual Drawdown (ft) Test 4 Step 1	Elapsed Time (min)	Residual Drawdown (ft) Test 4 Step 0	Residual Drawdown (ft) Test 4 Step 1
5	2.096	1.863	9.8	1.517	1.34
5.2	2.064	1.832	10	1.498	1.328
5.4	2.033	1.813	12	1.315	1.158
5.6	2.008	1.781	14	1.158	1.026
5.8	1.982	1.756	16	1.019	0.893
6	1.951	1.731	18	0.9	0.793
6.2	1.932	1.712	20	0.799	0.698
6.4	1.901	1.687	22	0.705	0.617
6.6	1.876	1.662	24	0.629	0.547
6.8	1.85	1.643	26	0.554	0.484
7	1.825	1.617	28	0.497	0.428
7.2	1.8	1.599	30	0.44	0.377
7.4	1.775	1.573	32	0.39	0.34
7.6	1.75	1.554	34	0.352	0.295
7.8	1.731	1.536	36	0.308	0.264
8	1.706	1.51	38	0.277	0.233
8.2	1.68	1.492	40	0.245	0.207
8.4	1.662	1.473	42	0.22	0.182
8.6	1.636	1.454	44	0.195	0.163
8.8	1.617	1.435	46	0.176	0.144
9	1.599	1.416	48	0.157	0.126
9.2	1.573	1.397	50	0.138	0.107
9.4	1.554	1.378	52	0.126	
9.6	1.536	1.366	54	0.113	

TABLE A.13 Slug test data for boring SB08 (effective saturated thickness = 10 ft: length of well = 10 ft; length of screen = 10 ft; casing radius = 0.04167 ft; borehole radius = 0.05469 ft; Kz/Kr = 1).

	Residual Drawdown (ft)				Residual Drawdown (ft)		
Elapsed Time (min)	Test 3 Step 0	Test 3 Step 1	Test 3 Step 2	Elapsed Time (min)	Test 3 Step 0	Test 3 Step 1	Test 3 Step 2
0	3.965	3.77	2.757	0.1333	0.132	0.126	0.094
0.0033	4.481	4.173	3.09	0.1366	0.132	0.126	0.088
0.0066	4.746	4.292	3.204	0.14	0.126	0.113	0.088
0.01	4.639	4.192	3.16	0.1433	0.12	0.113	0.082
0.0133	4.267	3.902	3.015	0.1466	0.113	0.107	0.082
0.0166	3.846	3.537	2.788	0.15	0.113	0.101	0.075
0.02	3.449	3.178	2.524	0.1533	0.107	0.101	0.075
0.0233	3.097	2.851	2.253	0.1566	0.101	0.094	0.069
0.0266	2.776	2.555	2.008	0.16	0.101	0.094	0.069
0.03	2.486	2.297	1.775	0.1633	0.101	0.088	0.069
0.0333	2.222	2.058	1.58	0.1666	0.094	0.088	0.063
0.0366	1.989	1.844	1.403	0.17	0.094	0.088	0.063
0.04	1.781	1.649	1.246	0.1733	0.088	0.082	0.063
0.0433	1.586	1.479	1.107	0.1766	0.088	0.082	0.057
0.0466	1.422	1.322	0.982	0.18	0.088	0.082	0.057
0.05	1.271	1.183	0.868	0.1833	0.082	0.075	0.057
0.0533	1.133	1.051	0.774	0.1866	0.082	0.075	0.057
0.0566	1.013	0.944	0.686	0.19	0.082	0.075	0.05
0.06	0.9	0.843	0.604	0.1933	0.075	0.069	0.05
0.0633	0.806	0.755	0.541	0.1966	0.075	0.069	0.05
0.0666	0.717	0.673	0.478	0.2	0.069	0.069	0.05
0.07	0.642	0.604	0.428	0.2033	0.069	0.069	0.044
0.0733	0.573	0.541	0.377	0.2066	0.069	0.063	0.044
0.0766	0.51	0.485	0.34	0.21	0.069	0.063	0.044
0.08	0.459	0.434	0.29	0.2133	0.063	0.063	0.044
0.0833	0.409	0.396	0.277	0.2166	0.063	0.063	0.044
0.0866	0.371	0.352	0.245	0.22	0.063	0.057	0.044
0.09	0.333	0.321	0.226	0.2233	0.063	0.057	0.038
0.0933	0.302	0.29	0.201	0.2266	0.057	0.057	0.038
0.0966	0.277	0.264	0.189	0.23	0.057	0.057	0.038
0.1	0.252	0.245	0.17	0.2333	0.057	0.05	0.038
0.1033	0.233	0.226	0.157	0.2366	0.057	0.05	0.038
0.1066	0.214	0.207	0.144	0.24	0.057	0.05	0.038
0.11	0.201	0.195	0.138	0.2433	0.05	0.05	0.031
0.1133	0.189	0.182	0.126	0.2466	0.05	0.05	0.031
0.1166	0.176	0.17	0.12	0.25	0.05	0.044	0.031
0.12	0.163	0.157	0.113	0.2533	0.05	0.044	0.031
0.1233	0.157	0.151	0.107	0.2566	0.05	0.044	0.031
0.1266	0.144	0.144	0.101	0.26	0.05	0.044	0.031
0.13	0.138	0.138	0.094	0.2633	0.044	0.044	0.031

TABLE A.13 (Cont.)

Elapsed Time (min)	Residual Drawdown (ft) Test 3 Step 0	Test 3 Step 1	Test 3 Step 2	Elapsed Time (min)	Residual Drawdown (ft) Test 3 Step 0	Test 3 Step 1	Test 3 Step 2
0.2666	0.044	0.044	0.031	0.35	0.031	0.025	0.019
0.27	0.044	0.044	0.031	0.3666	0.025	0.025	0.019
0.2733	0.044	0.038	0.031	0.3833	0.025	0.025	0.019
0.2766	0.044	0.038	0.025	0.4	0.025	0.025	0.012
0.28	0.044	0.038	0.025	0.4166	0.019	0.019	0.012
0.2833	0.044	0.038	0.025	0.4333	0.019	0.019	0.012
0.2866	0.038	0.038	0.025	0.45	0.019	0.019	0.012
0.29	0.038	0.038	0.025	0.4666	0.019	0.019	0.012
0.2933	0.038	0.038	0.025	0.4833	0.019	0.012	0.006
0.2966	0.038	0.038	0.025	0.5	0.012	0.012	0.006
0.3	0.038	0.031	0.025	0.5166	0.012	0.012	0.006
0.3033	0.038	0.031	0.025	0.5333	0.012	0.012	0.006
0.3066	0.038	0.031	0.025	0.55	0.012	0.012	0.006
0.31	0.038	0.031	0.025	0.5666	0.012	0.012	0.006
0.3133	0.038	0.031	0.025	0.5833	0.012	0.012	0.006
0.3166	0.038	0.031	0.019	0.6	0.012	0.012	0.006
0.32	0.031	0.031	0.019	0.6166	0.006	0.006	0.006
0.3233	0.038	0.031	0.019	0.6333	0.006	0.006	0.006
0.3266	0.038	0.031	0.025	0.65	0.006	0.012	0.006
0.33	0.031	0.031	0.019	0.6666	0.006	0.006	0.006
0.3333	0.031	0.031	0.025				

Appendix B:

Studies on the Degradation of Carbon Tetrachloride in the Presence of Zero-Valent Iron (February 2007)

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Studies on the Degradation of Carbon Tetrachloride in the Presence of Zero-Valent Iron (February 2007)

B.1 Introduction

Attempts at bioremediation of carbon tetrachloride contamination in groundwater have met with limited success, under either anaerobic (Dybas et al. 1998) or aerobic (Fogel et al. 1986; Henson et al. 1988) conditions. The difficulties seem to result from the toxicity of carbon tetrachloride to microorganisms, as well as the production of hazardous intermediates such as chloroform and methylene chloride. Recently, the possible use of nanoscale particles for *in situ* treatment of carbon tetrachloride contamination has been considered (Amonette 2006; Wang and Zhang 1997; Vogel et al. 1987). The theoretical potential benefits of nanoscale particles include their abilities to flow with groundwater and to promote rapid degradation of organic contaminants, in some cases immobilizing dissolved metals.

Nanoparticles of zero-valent iron (ZVI) have been considered for *in situ* remediation of carbon tetrachloride (Wang and Zhang 1997). Although the mechanisms at first glance might appear straightforward, more detailed observation reveals complex pathways and products resulting from reductive transformation of carbon tetrachloride. Depending on the type of iron present and the relative availability of electrons, hydrogen, nucleophiles, and even oxygen, products can range from toxic hexachloroethane, tetrachloroethene, trichloromethane, and dichloromethane to relatively innocuous carbon monoxide, carbon dioxide, and methane. In most circumstances, the dominant toxic product of reductive degradation of carbon tetrachloride is chloroform. Yields of chloroform in different iron-containing systems range from 20% to 80% (Amonette 2006).

Recent advances in applications of ZVI include products patented by Adventus Americas, Inc. (Freeport, Illinois). The Adventus product EHC® combines controlled release of carbon with ZVI for stimulation of *in situ* chemical reduction of carbon tetrachloride and other persistent organic compounds in groundwater. With this product, a number of physical, chemical, and microbiological processes combine to create very strong reducing conditions that stimulate rapid and complete dechlorination of organic solvents such as carbon tetrachloride.

The organic component of EHC (guar gum) is nutrient rich and hydrophilic. On the ZVI particles with their high surface area, this carbon source supports the growth of bacteria in groundwater. As the bacteria grow, oxygen is consumed, and the oxidation-reduction potential (ORP) in the groundwater decreases to values approaching -600 mV. At this potential, the small ZVI particles provide substantial reactive surface area and directly stimulate chemical dechlorination. In addition, indigenous heterotrophic bacteria that can ferment the carbon in the guar gum release a variety of volatile fatty acids that diffuse from the site of the fermentation into the groundwater plume and serve as electron donors supporting further bacterial reactions.

We report here the results of series of studies to evaluate the effectiveness — for the possible cleanup of contaminated sites in Nebraska and Kansas — of the Adventus ZVI products EHC and EHC-M (formulated for immobilization of metals, plus treatment of chlorinated solvents). A further goal is to understand the mechanisms of action of these products and the pathways they employ for the destruction of carbon tetrachloride.

In the work reported here, the effectiveness of the Adventus ZVI products EHC and EHC-M in reducing carbon tetrachloride was evaluated under laboratory conditions. Samples from a contaminated environmental area were collected to study their effect on the action of ZVI. Parameters monitored included pH, reaction rates, ORP, and the formation of organic products.

B.2 Experimental Setup

B.2.1 Instrumentation

The equipment used was a gas chromatograph (HP-6890, Agilent Technologies, Wilmington, Delaware, USA) with a mass spectrometer (HP-5892, Agilent). Heated lines were used to interface the autosampler unit (HP-2016, Agilent) to the gas chromatograph.

B.2.2 Batch Studies

For these laboratory studies, containers were filled with water, ZVI (Adventus EHC or EHC-M) material, and an aliquot of carbon tetrachloride. Deionized water (NANOpure® DIamond™, Barnstead International, Dubuque, Iowa, USA) was added, except as specified for particular experiments. A ratio of 100:1 for liquid volume to ZVI material volume was maintained throughout the experiments. When soil was present, the ratio of soil to ZVI material was 5:1. Samples were placed directly in the autosampler, and measurements were made from time zero to a maximum of 220 hr. One sample containing no ZVI was used as a reference standard in each experiment.

B.2.3 Reagents

A standard solution of carbon tetrachloride at 100 μg/mL in methanol (Chem Service, West Chester, Pennsylvania, USA) was used to prepare a solution with an initial analyte concentration of 100 ppb. These solutions meet or exceed all requirements and guidelines set forth in 40 Code of Federal Regulations Part 136. The stock solutions were stored at 4°C, and dilutions were prepared daily as needed. All standard solutions and dilutions were made by using Ultra Resi-Analyzed™ methanol (J.T. Baker, Phillipsburg, New Jersey, USA).

B.2.4 Environmental Samples

Soil samples from Centralia, Kansas, used in these experiments came from monitoring well MW02, at a depth of 51 ft BGL. This is the location where the major contamination has been found in the aquifer at the Centralia site. Prior to its introduction into batch experimental mixtures, the dry core soil sample was homogenized by using a size 16 mesh (0.0394 in.). Water from Centralia was collected from a drinking water well in the area.

B.3 Results and Discussion

In experiments using only ZVI to decompose carbon tetrachloride to chloroform, no other product in the dechlorination path has ever been observed (Amonette 2006). Bioremediation is an alternate route for decomposition of carbon tetrachloride, but its mechanisms are complex, and the pathways are difficult to follow. For example, a study using bacteria in an iron-nitrate environment had some positive results in the laboratory, but the conditions were difficult to reproduce in the field. The application of ZVI would have a major advantage if the nanoparticles could set up an environment capable of completely reducing carbon tetrachloride to harmless products.

B.3.1 Ability of ZVI Material to Reduce Carbon Tetrachloride

In our tests of degradation by ZVI, carbon tetrachloride was reduced at different rates, depending on the conditions of the experiment (Figures B.1-B.6, for example). The results provide evidence of dechlorination and formation of chloroform (typically accounting for 10-20% of the initial amount of carbon tetrachloride). The rest of the carbon tetrachloride went into a different pathway, with possible formation of relatively harmless products such as formic acid and carbon monoxide. When carbon tetrachloride disappeared almost completely from the solution, the small amount of chloroform remaining decomposed to form dichloromethane, as observed in Figure B.3.

B.3.2 Effects of pH on the Reduction of Carbon Tetrachloride by ZVI

Our initial experiment, performed with EHC-M, deionized water, and standard solutions under normal laboratory conditions, achieved less than 20% decomposition of the total carbon tetrachloride introduced, in more than 90 hr of incubation (Figure B.1).

Iron characteristically remains in lower valance states at lower pH values. At neutral pH values, iron is easily oxidized to form iron oxide. To observe the effect of pH on the decomposition of carbon tetrachloride by ZVI, we added hydrochloric acid to decrease the pH of the solution. Figures B.2 and B.3 show the decomposition of carbon tetrachloride, with EHC and EHC-M respectively, in solutions at pH = 1. Both figures demonstrate rapid decomposition of carbon tetrachloride, within hours of mixing. In less than one day, almost 80% of the carbon tetrachloride introduced was decomposed, and minor production of chloroform was observed. Chloroform was produced not in a 1:1 ratio, as expected. After 90 hr, formation of a small amount (less than 1 ppb) of dichloromethane was observed.

To continue evaluation of the effect of pH on the degradation of carbon tetrachloride by ZVI, another experiment was performed with an acetic acid buffer at pH = 3.1. Results for EHC-M are shown in Figure B.4. Incubation for more than 140 hr demonstrated a slower carbon tetrachloride decomposition rate than in experiments conducted at pH = 1 (Figures B.2 and B.3). Chloroform and dichloromethane were produced in small amounts (Figure B.4).

The reaction half-lives at various pH levels are shown in Table B.1. The results indicate that the half-life of the reaction for decomposition of carbon tetrachloride increases with increasing pH. Thus, pH plays an important role in degradation of carbon tetrachloride by ZVI.

B.3.3 Decomposition of Carbon Tetrachloride by ZVI with Soil and Water from a Contaminated Site

Soil samples for this study were selected from the core for monitoring well MW02 at Centralia, at the center of the contamination plume at 51 ft BGL. In addition, water from the aquifer system at Centralia was used to mimic conditions in the field.

One reaction mixture for this study contained soil from the contaminated area at Centralia and ZVI material (EHC-M) in a 5:1 ratio, with sufficient deionized water (pH = 5.2) to achieve a liquid to EHC-M ratio of approximately 100:1 (by volume). As Figure B.5 shows, the reaction started slowly, with only small changes in the concentration of carbon tetrachloride over time. Under these conditions, the half-life for carbon tetrachloride decomposition was 73 hr (Table B.1).

A subsequent experiment combined EHC-M, carbon tetrachloride, and soil and water (pH = 7.2) from the contaminated area. Figure B.6 shows the results. In this case, the reaction rate was even slower than with deionized water (pH = 5.2; Figure B.5), with a half-life of 145 hr (Table B.1).

The behavior observed in Figures B.5 and B.6 is consistent with the behavior expected for ZVI coated with organic material. The results suggest that at the beginning, some of the free iron reacted to produce chloroform, but at longer times the decomposition was driven mainly by bacteria in the soil and water. The bacteria would use the organic material surrounding the ZVI nanoparticles as a food source, creating better conditions for the reaction of iron with carbon tetrachloride. The result was accelerated decomposition later in the incubation period, as shown in Figures B.5 and B.6. Almost 90% of the original carbon tetrachloride was decomposed in 140-160 hr in these two experiments.

Our hypothesis is that bacteria in the soil and water added to the reaction mixture used the organic material coating the iron nanoparticles to accomplish the following:

- Decrease the oxygen levels
- Decrease the ORP, setting up a reducing environment
- Release a variety of volatile fatty acids that could be used as electron donors
- Decrease the pH of the solution

To understand the mechanism of degradation of carbon tetrachloride by EHC and EHC-M, we studied changes in the pH and ORP of the system (Figure B.6) containing ZVI, carbon tetrachloride, and soil and water from the contaminated site. Figure B.7 shows changes in pH with time. The overall change in pH, from 7.2 to 6.8, is not significant enough to explain the change in the reaction rate and the rapid decomposition of carbon tetrachloride observed in the presence of soil and water from the contaminated area (Figure B.6). Figure B.8 shows the change of ORP with time. In this case, the ORP seems to increase and decrease at random. Similar behavior has been reported by Adventus (E. Dimitrovic, unpublished data).

The results for pH and ORP suggest that decomposition of carbon tetrachloride by ZVI occurs through a complex mechanism. The bacteria appear to improve conditions for the reaction, but other changes at the molecular level might also be involved. More than 90% of the carbon tetrachloride was decomposed in our tests with soil from the contaminated area at Centralia (Figures B.5 and B.6).

B.3.4 Effect of Sterilization of Soil and Water on Carbon Tetrachloride Decomposition by ZVI

To determine whether active bacterial metabolism was supporting the decomposition of carbon tetrachloride by ZVI in the experiments illustrated in Figures B.5 and B.6, we added sterilized soil and water from the contaminated site to an experimental batch with carbon tetrachloride and EHC-M. If bacteria in the native soil and water samples dramatically affect the decomposition of carbon tetrachloride by ZVI, then sterilizing the soil and water should slow or even prevent decomposition.

Soil samples were sterilized by heating in an oven to 80°C on four consecutive days. Water samples were sterilized by boiling for 1 hr at 100°C. The EHC-M material is not sterile and was used without treatment. Heating EHC-M can cause decomposition of the material and oxidize the iron, therefore reducing the effectiveness of the product.

To the reaction mixture containing EHC-M, sterilized soil, and boiled water, an aliquot of carbon tetrachloride was added. Figure B.9 shows the results of analyses for volatile organic compounds over more than 220 hr of monitoring. The plot is similar to the one obtained for a simultaneously conducted batch experiment with EHC-M and unsterilized soil and water (Figure B.10). Formation of gas was observed in both reaction systems.

These results do not rule out a role for bacteria in the decomposition of carbon tetrachloride by ZVI; however, the results do demonstrate that the decomposition is not dependent on the presence of live bacteria from the contaminated site. Clearly, ZVI (EHC-M) decomposed the carbon tetrachloride without the help of active bacteria from the contaminated site (Figure B.9). The results demonstrate significant complexity in the reaction system.

B.3.5 Pathway for Carbon Tetrachloride Decomposition

As stated in Section B.1, at first glance the mechanisms for degradation of carbon tetrachloride by ZVI appear straightforward, but more detailed observation reveals complex pathways and products. The degradation process is not well understood, and we are continuing to investigate the pathways.

One important factor is that the ZVI products tested can decompose carbon tetrachloride to compounds other than chloroform (the result typically observed in other studies). The products tested release (1) organic material to change the reaction conditions and (2) ZVI as a chemical reducing agent.

The ZVI products tested initiate a number of physical, chemical, and microbiological processes that combine to create very strong reducing conditions *in situ* and stimulate rapid and complete dechlorination of carbon tetrachloride. These processes include (1) biological reduction (consumption of oxygen and other electron acceptors); (2) chemical reduction of the oxidized pollutants, either directly by the reduced metals or indirectly via the formation of hydrogen that is used by bacteria as an electron donor; and (3) direct chemical oxidation due to ZVI oxidation-reduction reactions, via beta-elimination reactions and additional oxygen scavenging that decreases the ORP of the system.

Chemical routes for carbon tetrachloride degradation are usually kinetically controlled, and these types of process will play an important role in the decomposition. Carbon tetrachloride produces the trichloromethyl radical, which is transformed to yield chloroform under mild reducing conditions, or carbon monoxide and formic acid if the reducing conditions are stronger (due to a combination of effects). Possible mechanisms for chemical degradation in our ZVI-carbon tetrachloride systems are as follows:

Possible Mechanism 1:

$$CCl_4 + e^- \rightarrow Cl_3\text{-}C\cdot \text{ (trichloromethyl radical) } + Cl^- \qquad \text{(B.1a)}$$

$$Cl_3\text{-}C\cdot + H^+ + e^- \rightarrow CHCl_3 \text{ (chloroform)} \qquad \text{(B.1b)}$$

$$CHCl_3 + H^+ + 2\ e^- \text{ (strong reductant) } \rightarrow Cl_2CH_2 + Cl^- \qquad \text{(B.1c)}$$

Possible Mechanism 2:

$$CCl_4 + e^- \rightarrow Cl_3\text{-}C\cdot \text{ (trichloromethyl radical) } + Cl^- (e^-) \qquad \text{(B.2a)}$$

$$Cl_3\text{-}C\cdot + e^- \rightarrow Cl_2\text{-}C{:} + Cl^- \qquad \text{(B.2b)}$$

$$Cl_2\text{-}C{:} + H_2O \rightarrow C{\equiv}O \text{ (carbon monoxide) } + 2\ HCl \qquad \text{(B.2c)}$$

$$Cl_2\text{-}C{:} + 2\ H_2O \rightarrow HCOOH \text{ (formic acid) } + 2\ HCl \qquad \text{(B.2d)}$$

B.3.6 Difference between EHC and EHC-M

The main difference between the Adventus products EHC and EHC-M is that EHC-M contains a ligand that can trap metals that might otherwise become free in the environment. For example, arsenic, a natural element in soils, can become free during remediation processes and increase the concentration of arsenic in the groundwater. The ligand in EHC-M can capture the arsenic and avoid movement of the element into the water system.

The two Adventus products were equally effective in decomposing carbon tetrachloride in laboratory samples, as illustrated in Figures B.11 and B.12.

B.3.7 Testing for Lead and Arsenic Contaminants in the Adventus Products

A concern raised by the KDHE is the environmental effect of possible lead and arsenic contaminants in the EHC and EHC-M products. These materials and the guar gum used to coat the ZVI nanoparticles were analyzed in the laboratory for lead and arsenic. Results are presented in Table B.2.

According to the OSWER 9355.4-12 (1994 interim guidance) and the U.S. Environmental Protection Agency, lead concentrations are considered hazardous if they are above 400 mg/kg in bare soil in children's play areas or above 1,200 mg/kg in other places. Typical U.S. soil concentrations range from 10 to 30 mg/kg. The lead values found in the ZVI materials (10.3 mg/kg and 18.5 mg/kg) are within the background levels. Arsenic was not found in the ZVI samples. The guar gum contained no detectable arsenic or lead.

B.4 Conclusions

Our studies on the use of the Adventus ZVI products EHC and EHC-M showed that the materials can reduce the concentrations of carbon tetrachloride in samples prepared in the laboratory. In use, these products combine a number of physical, chemical, and microbiological processes to create very strong reducing conditions that stimulate rapid and complete dechlorination of carbon tetrachloride.

Preliminary results for batch experiments using soil and water from the Centralia, Kansas, contaminated site showed that carbon tetrachloride can be decomposed by the ZVI products in the presence of the environmental materials. The reaction began slowly, but it accelerated as appropriate conditions were established by the combination of factors mentioned previously. Concentrations of carbon tetrachloride decreased by more than 90% in our laboratory studies.

The ZVI technology offers the possibility of *in situ* remediation of carbon tetrachloride at contaminated sites. In the laboratory, the Adventus products showed promise, but conditions are not the same in the field. Subjecting the ZVI product to a field pilot study would demonstrate whether suitable conditions and decreased carbon tetrachloride concentrations can be achieved at a contaminated site.

TABLE B.1 Carbon tetrachloride degradation half-life and pH in EHC batch tests.

Figure	pH	Half-life (hr)	Description
B.2, B.3	1.1	6	Hydrochloric acid
B.4	3.1	12	Acetic acid buffer
B.5	5.2	73	Soil[a] + deionized water
B.6, B.9, B.10, B.12	7.2	77-145	Soil[a] + water from Centralia

[a] Soil from aquifer zone at Centralia (MW02, 51 ft BGL).

TABLE B.2 Concentrations of lead and arsenic in Adventus products.

Sample	As (mg/kg)	Pb (mg/kg)
Guar gum	ND[a]	ND[b]
EHC	ND[a]	18.5
EHC-M	ND[a]	10.3

[a] Arsenic not detected at 0.32 mg/kg.

[b] Lead not detected at 0.21 mg/kg.

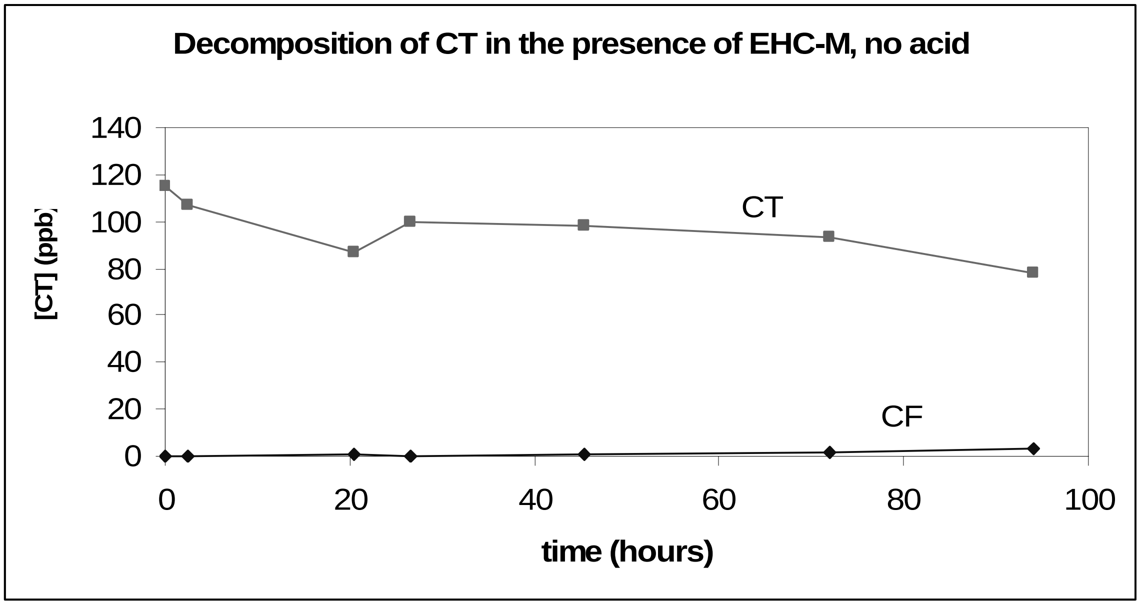

FIGURE B.1 Reaction components: Deionized water, EHC-M, carbon tetrachloride.

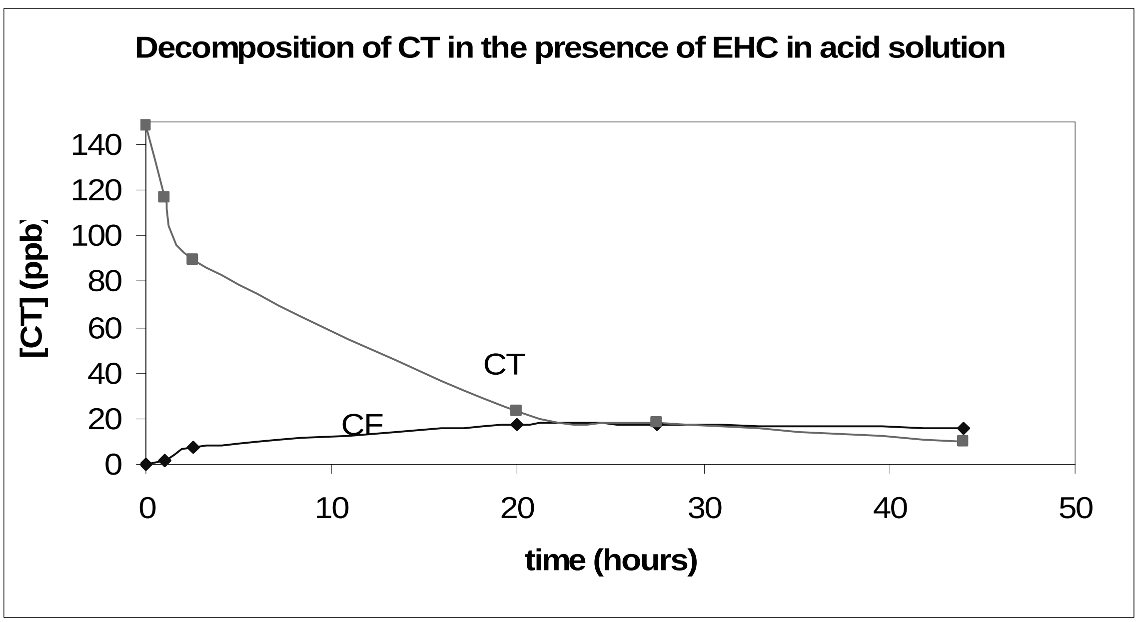

FIGURE B.2 Reaction components: Deionized water, EHC, carbon tetrachloride, hydrochloric acid (pH = 1).

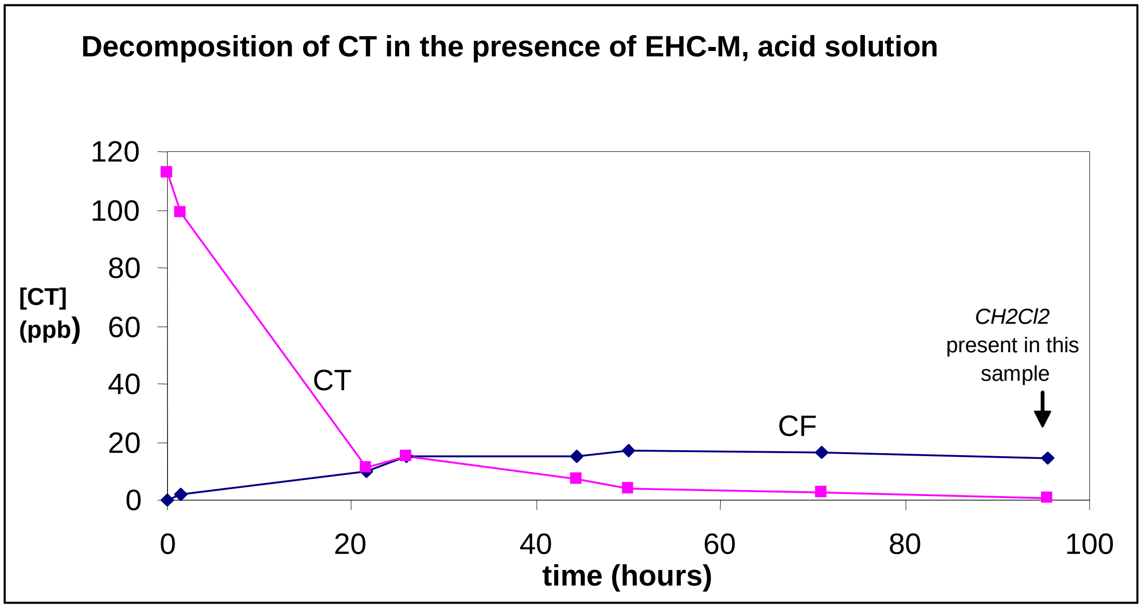

FIGURE B.3 Reaction components: Deionized water, EHC-M, carbon tetrachloride, hydrochloric acid (pH = 1).

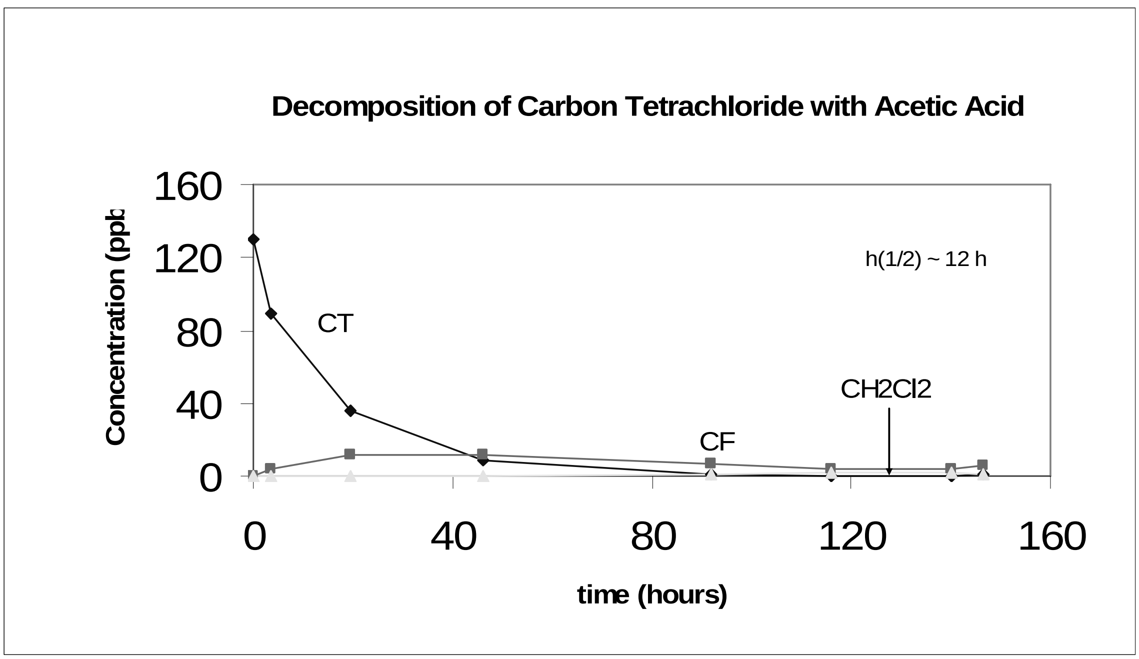

FIGURE B.4 Reaction components: Deionized water, EHC-M, carbon tetrachloride, acetic acid buffer (pH = 3.1).

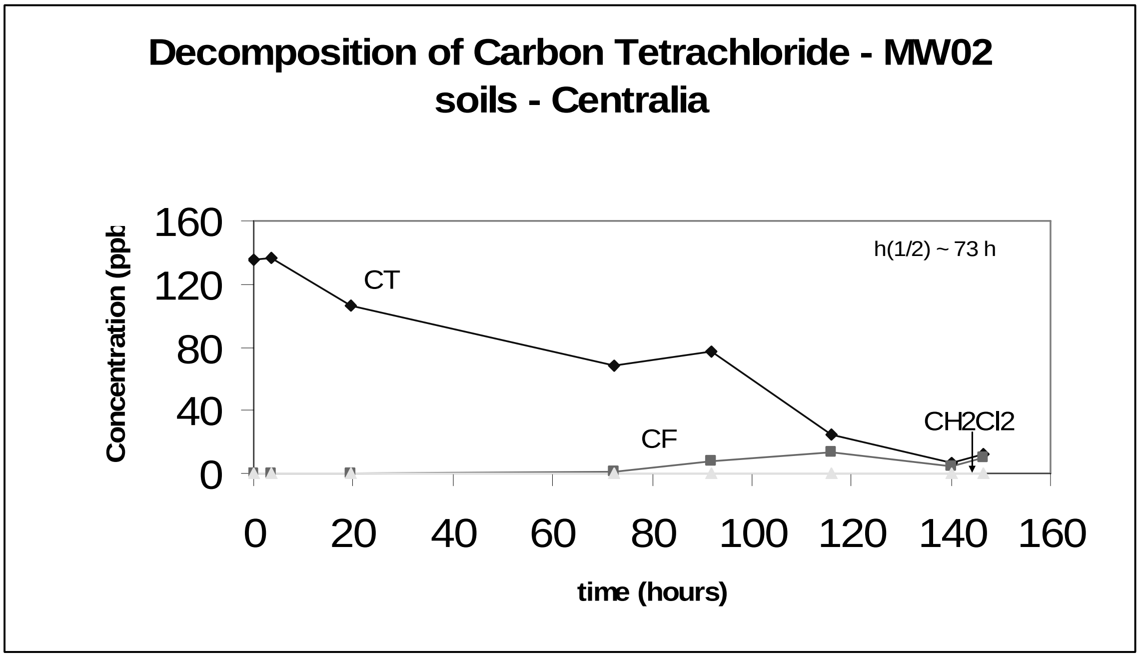

FIGURE B.5 Reaction components: Deionized water (pH = 5.2), EHC-M, Centralia soil, carbon tetrachloride.

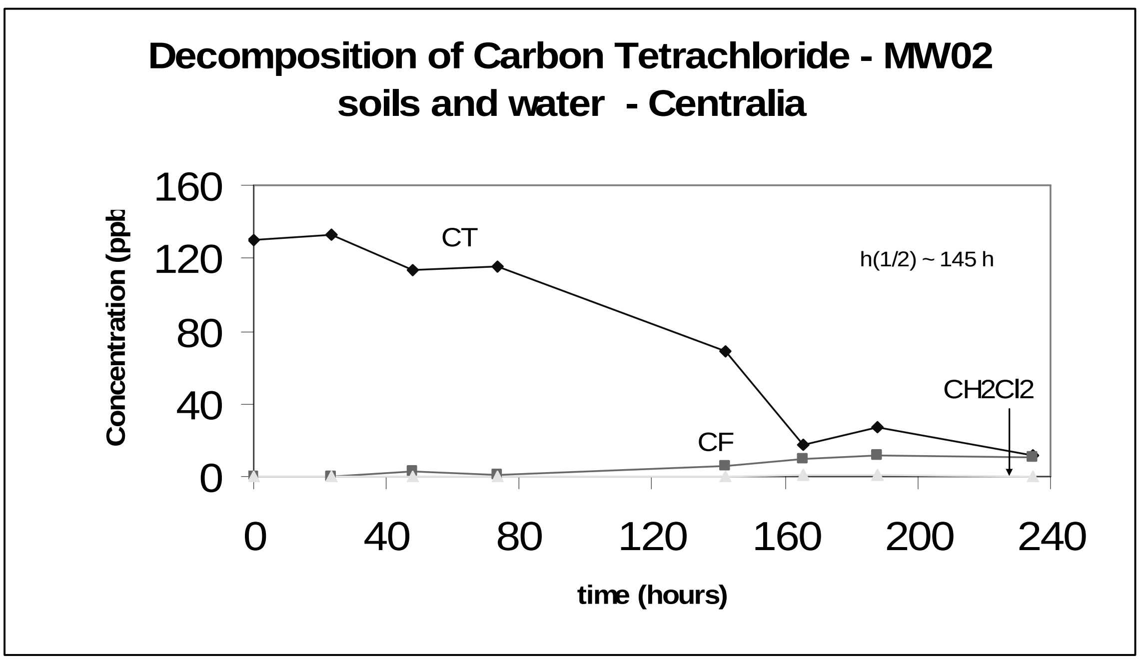

FIGURE B.6 Reaction components: Centralia water (pH = 7.2), EHC-M, Centralia soil, carbon tetrachloride.

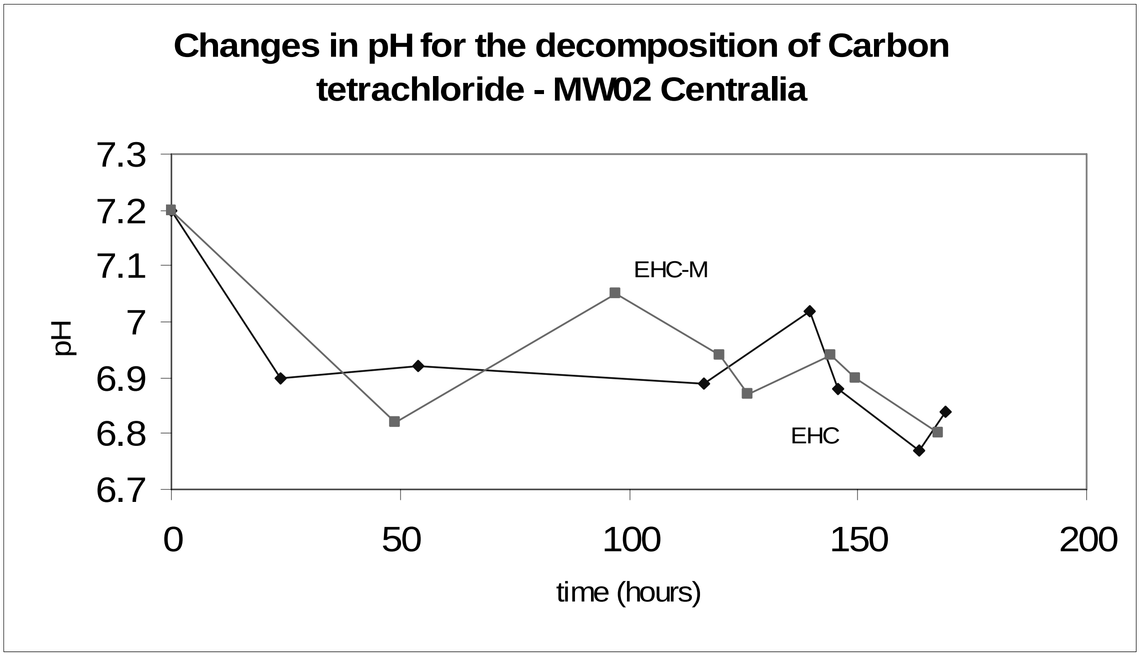

FIGURE B.7 Reaction components: Centralia water (pH = 7.2), EHC or EHC-M, Centralia soil, carbon tetrachloride.

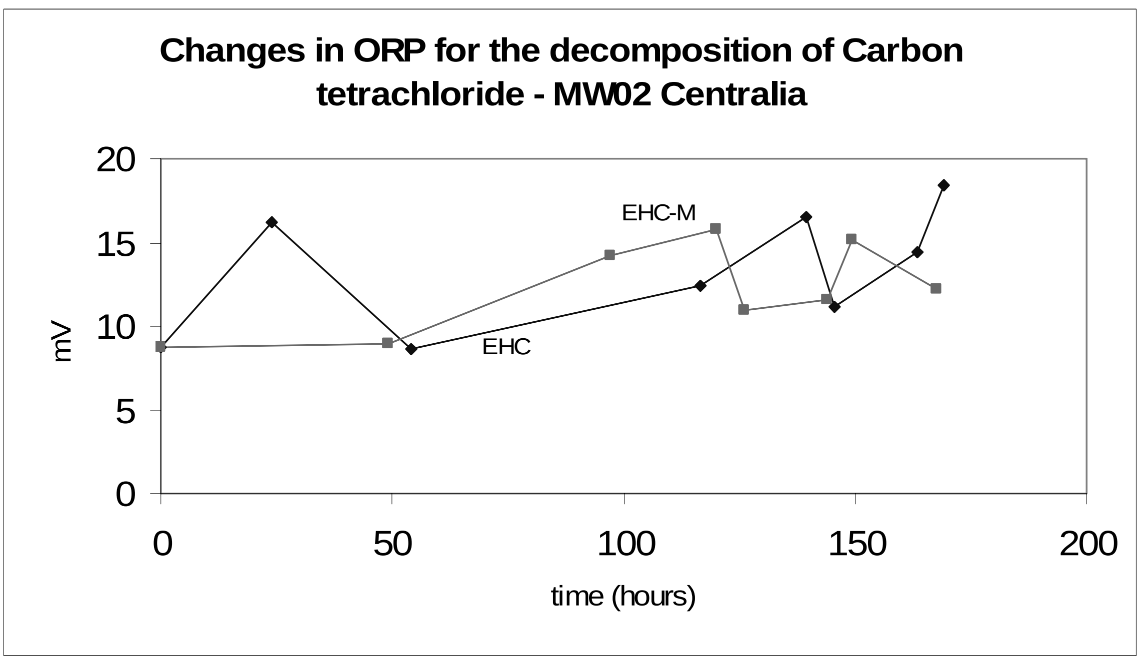

FIGURE B.8 Reaction components: Centralia water (pH = 7.2), EHC or EHC-M, Centralia soil, carbon tetrachloride.

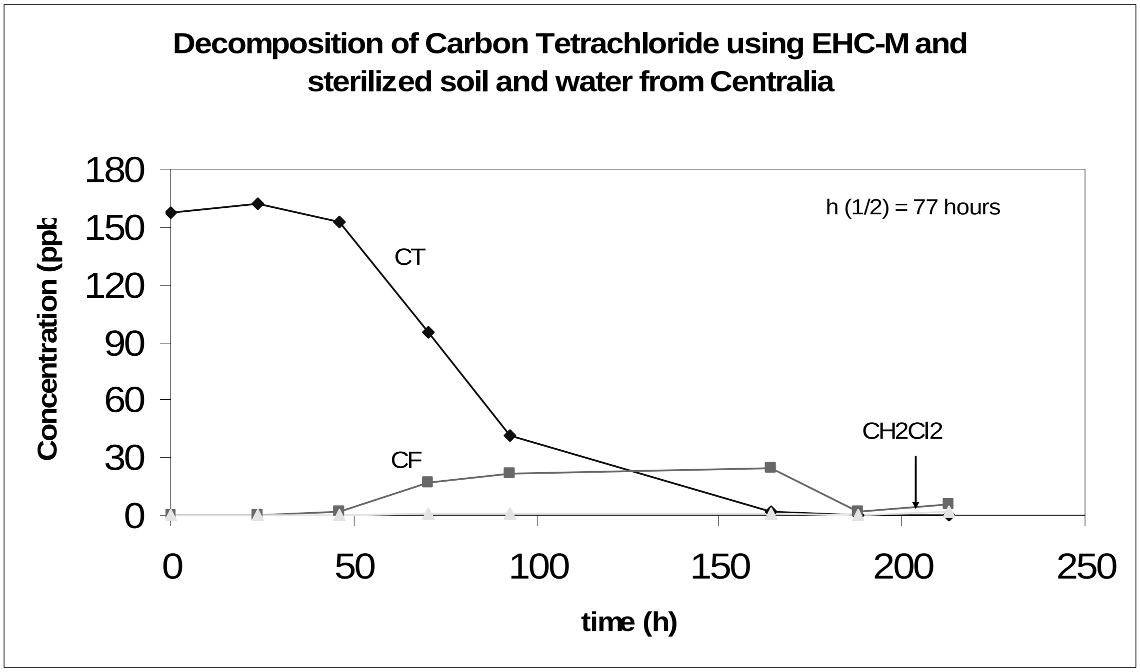

FIGURE B.9 Reaction components: Boiled Centralia water, EHC-M, sterilized Centralia soil, carbon tetrachloride.

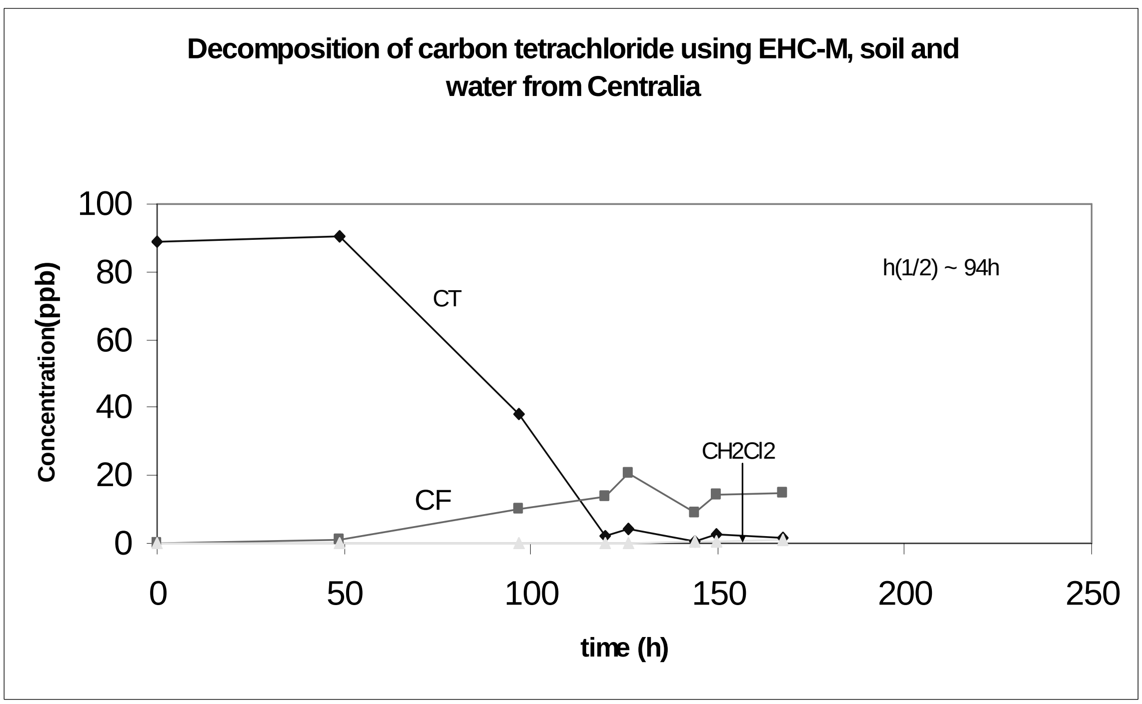

FIGURE B.10 Reaction components: Unboiled Centralia water, EHC-M, unsterilized Centralia soil, carbon tetrachloride.

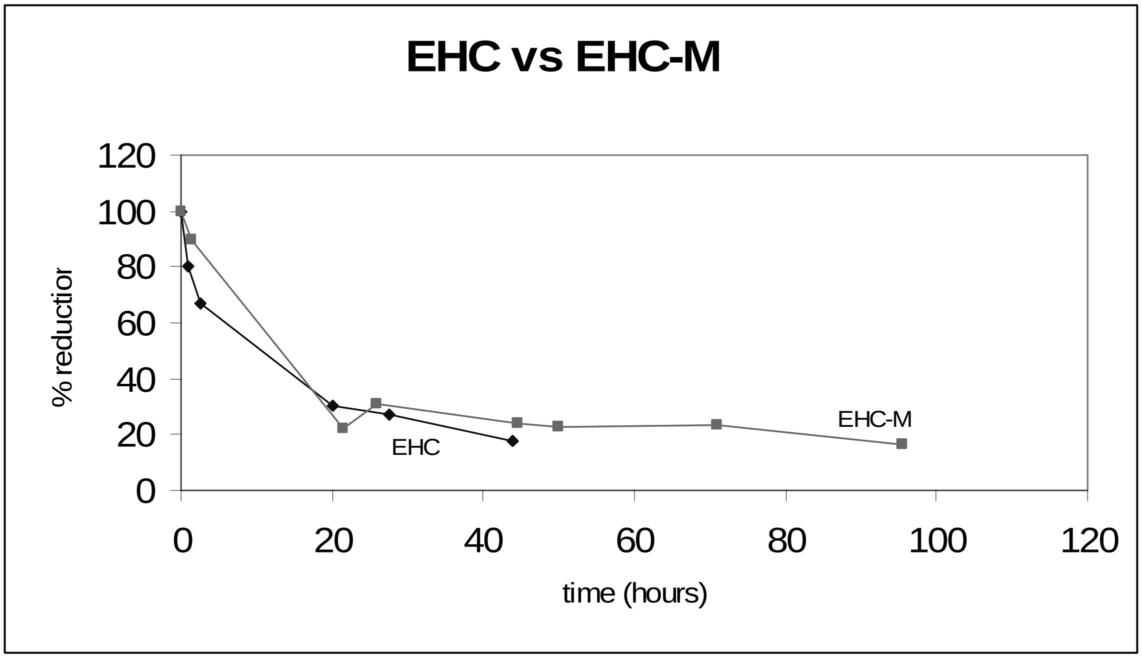

FIGURE B.11 Reaction components: Deionized water, EHC or EHC-M, carbon tetrachloride, hydrochloric acid (pH = 1).

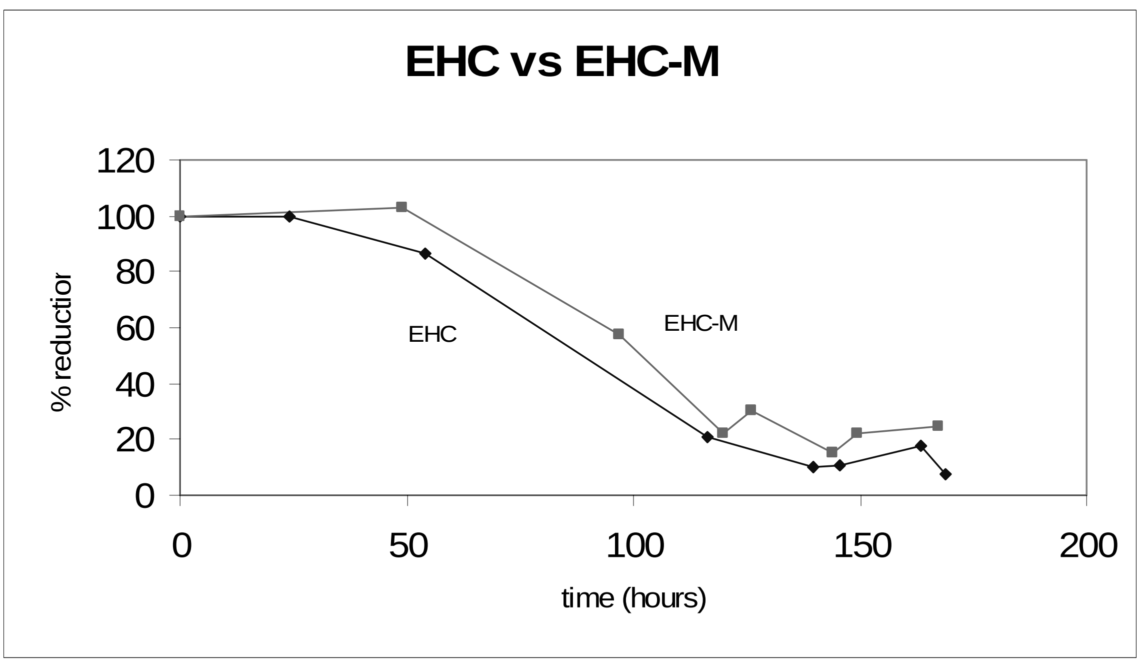

FIGURE B.12 Reaction components: Centralia water, EHC or EHC-M, Centralia soil, carbon tetrachloride.

Appendix C:

Material Safety Data Sheets for EHC and EHC-A

ADVENTUS
Proven Soil, Sediment, and Groundwater Remediation Technologies

Safety Data

MATERIAL SAFETY DATA SHEET: **EHC™**

1. PRODUCT IDENTIFICATION: EHC™

PRODUCT USE: Bioremediation product for the remediation of contaminated soil and groundwater only. Not for use in potable drinking water.

MANUFACTURER:

Adventus Remediation Technologies
1345 Fewster Drive
Mississauga, Ontario
L4W 2A5

EMERGENCY PHONE:

Office Hours: 905-273-5374
After Hours: 416-457-9491

TRANSPORTATION OF DANGEROUS GOOD CLASSIFICATION:
Not Regulated

WHMIS CLASSIFICATION:
Not Regulated

CONTAINMENT HAZARD:
Any vessel that contains wet EHC or EHC and water must be vented due to potential pressure build up from fermentation gasses.

2. INGREDIENTS

CHEMICAL NAME:	CAS#	TLV (mg/m3)	LD low (mg/Kg)	% in Product
Organic Amendment	N/D	N/E	N/E	52 - 82
Iron	7439-89-6	5 (as iron oxide fume)	N/E	18 - 48

3. PHYSICAL DATA

Physical state	Solid	Melting point	1371-1480°F
Odour threshold	N/A	Boiling point	3000°C
Density	0.75 Kg/L	Vapour pressure (mm Hg)	1 @ 1787°C
pH	N/A	Vapour density (air=1)	N/A
Solubility in water	Insoluble	Evaporation rate	N/A
Coeff. of water/oil	N/A		
Appearance & odour	Odourless, Tan/Brown Flakes		

4. FIRE AND EXPLOSION HAZARD DATA

FLASH POINT (Deg. C PMCC): N/A

	LOWER	UPPER
FLAMMABLE LIMITS IN AIR % BY VOLUME:	N/A	N/A

ADVENTUS
Proven Soil, Sediment, and Groundwater Remediation Technologies

Safety Data

MATERIAL SAFETY DATA SHEET: **EHC™** **Page:** 2 of 3

AUTO IGNITION TEMP (Deg. C): N/A

EXTINGUISHING MEDIA: Dry chemicals or sand or universal type foam.

SPECIAL PROCEDURES:
Firefighters should wear SCBA and protective clothing.

UNUSUAL FIRE AND EXPLOSION HAZARDS:

Dust can present fire and explosion hazards when exposed to fire, chemical reaction, or contact with powerful oxidizers.

5. REACTIVITY DATA

STABILITY (NORMAL COND.):
Stable: X **Unstable:**

CONDITIONS TO AVOID: Contact with powerful oxidizers such as strong acids.

INCOMPATIBILITY (Materials to Avoid): Powerful oxidizers such as strong acids.

HAZARDOUS DECOMPOSITION PRODUCTS: Hydrogen, Carbon monoxide, Carbon dioxide.

6. TOXICOLOGICAL PROPERTIES

ROUTE OF ENTRY:
Inhalation
Ingestion (not likely)

HEALTH HAZARDS:

Acute overexposure may cause eye, nose, mouth and skin irritation.

Carcinogenicity:	No Information Available
Signs and Symptoms of Exposure:	No Information Available
Medical Conditions Generally Aggravated by Exposure:	No Information Available

7. PREVENTIVE MEASURES

PERSONAL PROTECTIVE EQUIPMENT:

Eye Protection: X **Gloves:** X **Clothing:**

RESPIRATORY PROTECTION:

Use dust mask in severe conditions.
Use good housekeeping practices to keep dust to a minimum.

VENTILATION REQUIREMENTS:
Not normally required.

SPILL AND LEAK PROCEDURES:
Sweep up and return to container.

WASTE DISPOSAL:
Sanitary landfill. Follow Federal, State and Local guidelines.

HANDLING PROCEDURES:
Wear safety glasses for normal use. Avoid generating excessive dust, wear dust mask in severe conditions.

STORAGE REQUIREMENTS:
Do not store near powerful oxidizers such as strong acids.
Keep dry.
Any vessel that contains wet EHC or EHC and water must be vented due to potential pressure build up from fermentation gasses.

SPECIAL HANDLING INFORMATION:
Treat as a nuisance dust

8. FIRST AID MEASURES

INHALATION: Remove to fresh air. Seek medical attention.
INGESTION: Seek medical attention.
SKIN CONTACT: Brush off excess. Wash with soap and water.
EYE CONTACT: Flush with running water. Seek medical attention.

9. OTHER INFORMATION

None

10. PREPARATION INFORMATION

Prepared By:	Adventus Remediation Technologies	Date Prep./Rev.:	7/5/07
	1345 Fewster Drive	Print Date:	7/5/07
	Mississauga, Ontario	Phone:	905-273-5374
	L4W 2A5	Fax:	905-273-4367

Definitions:

N/D - No Data	N/A - Not Applicable	N/E - Not Established	< - Less than
A= Oral rat LD50	B= Oral rat	LD low C= Oral LD50/LD low other animal	> - Greater than
D= Estimated 1000	E= Arbitrary 2000	F= Other route prefix	
C= Ceiling limit			

EHC™ is a trademark of Adventus Intellectual Property Inc.

ADVENTUS
Proven Soil, Sediment, and Groundwater Remediation Technologies

Safety Data

MATERIAL SAFETY DATA SHEET: **EHC-A™**

1. PRODUCT IDENTIFICATION: EHC-A™
PRODUCT USE: For the remediation of contaminated groundwater only. Not for use with potable drinking water.

MANUFACTURER:

Adventus Remediation Technologies
1345 Fewster Drive
Mississauga, Ontario
L4W 2A5

EMERGENCY PHONE:

Office Hours: 905-273-5374
After Hours: 416-457-9491

TRANSPORTATION OF DANGEROUS GOOD CLASSIFICATION:
Not Regulated

WHMIS CLASSIFICATION:
Not Regulated

CONTAINMENT HAZARD:
Any vessel that contains wet EHC or EHC and water must be vented due to potential pressure build up from fermentation gasses.

2. INGREDIENTS

CHEMICAL NAME:	**CAS#**	**TLV (mg/m3)**	**LD low (mg/kg)**
Organic Amendment	N/D	N/E	N/E
Ferrous Sulfate	7782-63-0	N/E	319 (oral rat)

3. PHYSICAL DATA

Physical state	Solid	Freezing point	0°C
Odour threshold	N/A	Boiling point	N/A
Density	1.08 kg/L	Vapour pressure (mm Hg)	N/A
pH	N/A	Vapour density (air=1)	N/A
Solubility in water	Soluble	Evaporation rate	N/A
Coeff. of water/oil	N/A		
Appearance & odour	White Powder, mild sweet odour		

4. FIRE AND EXPLOSION HAZARD DATA

FLASH POINT (Deg. C): 250

	LOWER	**UPPER**
FLAMMABLE LIMITS IN AIR % BY VOLUME:	N/A	N/A
AUTO IGNITION TEMP (Deg. C):	N/A	

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Proven Soil, Sediment, and Groundwater Remediation Technologies

Safety Data

EXTINGUISHING MEDIA: Foam, CO2, Dry chemicals or water.

SPECIAL PROCEDURES: N/A

UNUSUAL FIRE AND EXPLOSION HAZARDS: N/A

5. REACTIVITY DATA

STABILITY (NORMAL COND.):
Stable: X **Unstable:**

6. TOXICOLOGICAL PROPERTIES

ROUTE OF ENTRY:
Inhalation
Ingestion
Skin
Eyes

HEALTH HAZARDS:

Inhalation: Dust irritation, respiratory ailments may be aggravated by dust (allergen)

Skin Contact: Dust irritation

Eye Contact: Dust irritation

Potential Allergen: This product is a potential allergen due to the presence of milk proteins.

EMERGENCY FIRST AID:

Skin: Wash with soap and water and rinse with water

Eye: Rinse with water, see physician if necessary

Inhalation: Not applicable

Ingestion: Do not provoke vomiting. See physician if necessary

7. PREVENTIVE MEASURES

PERSONAL PROTECTIVE EQUIPMENT:

Gloves: PVC or rubber
Clothing: Good manufacturing practices

ADVENTUS
Proven Soil, Sediment, and Groundwater Remediation Technologies

Safety Data

Respiratory: Dust mask

Eye: Safety glasses

Footwear: Safety shoes

Engineering Controls: Not applicable

SPILL AND LEAK PROCEDURES:
Sweep up or shovel up and dispose of in a suitable container. Clean area with detergent and rinse.

WASTE DISPOSAL:
In accordance with local, provincial, state and federal regulations

HANDLING PROCEDURES:
Not applicable.

STORAGE REQUIREMENTS:
Keep away from heat source, store in cool storage (20°C/68°F) with a relative humidity of less than 50%.
Avoid storing near strong smelling products.
Any vessel that contains wet EHC or EHC and water must be vented due to potential pressure build up from fermentation gasses.

8. PREPARATION INFORMATION

Prepared By:	Adventus Remediation Technologies	Date Prep./Rev.:	10/26/05
	1345 Fewster Drive	Print Date:	10/26/05
	Mississauga, Ontario	Phone:	905-273-5374
	L4W 2A5	Fax:	905-273-4367

Definitions:

N/D - No Data	N/A - Not Applicable	N/E - Not Established	< - Less than
A= Oral rat LD50	B= Oral rat	LD low C= Oral LD50/LD low other animal	> - Greater than
D= Estimated 1000	E= Arbitrary 2000	F= Other route prefix	
C= Ceiling limit			

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managed by UChicago Argonne, LLC